Optoelectronic Tweezers for Cell and Nanoparticle Manipulation

Ming C. Wu
Electrical Engineering and Computer Sciences Dept.
University of California, Berkeley
Berkeley, CA 94720, U.S.A.
wu@eecs.berkeley.edu

***Abstract*—Optoelectronic tweezers (OET) is a new tool for non-invasive, parallel manipulation of cells and/or micro/nanoparticles. Based on light-induced dielectrophoresis, OET can trap and sort colloidal particles, biological cells, nanowires and nanoparticles using a digital light projector. In this paper, we will present the principle and recent experimental results of OET.**

Keywords-Optoelectronic tweezers, optical minpulation, light-induced dielectrophorosis, dielectrophorosis

I. INTRODUCTION

The ability to manipulate biological cells, micro- and nanoscopic particles plays an important role in many biological and colloidal science applications. However, conventional manipulation techniques - including optical tweezers, electrophoresis, dielectrophoresis (DEP), magnetic tweezers, acoustic traps, and hydrodynamic flows - cannot achieve high resolution and high throughput at the same time. We have proposed a new technique called optoelectronic tweezers (OET) that permits parallel addressing of individual particles over a large area (Fig. 1) [1]. Using optically induced DEP, OET combines the aspects of both optical tweezers and DEP. The optical power density requirement (~ 0.1 to 10 W/cm2) is significantly lower than that of optical tweezers (by four to five orders of magnitude), thanks to the optoelectronic gain in OET. These optical intensities can be achieved by a computer projector, allowing the creation of complex optical manipulation patterns. OET manipulation has been demonstrated on a variety of microparticles including polystyrene beads [1-3], E. coli bacteria [4], red and white blood cells [3], HeLa cells [2, 5], and yeast cells [6]. Particle and cell sorting [2, 7] and concentration [8, 9] have also been demonstrated. By controlling bias voltage, we have also shown it is possible to perform light-induced electroporation [10]. A detailed description of the OET devices can be found in [2, 3]. Cell manipulation in highly conductive physiological buffer solution is achieved by replacing amorphous Si photoconductor with phototransistor, which has 100x higher photoconductivity [11]. Recently, OET has been extended to manipulate nanoscopic particles, including semiconducting and metallic nanowires [12] and gold nanoparticles with size as small as 60 nm [13]. Combining OET with surface immobilization techniques, a novel technique called NanoPen has been reported for flexible light "printing" of gold nanoparticles [14].

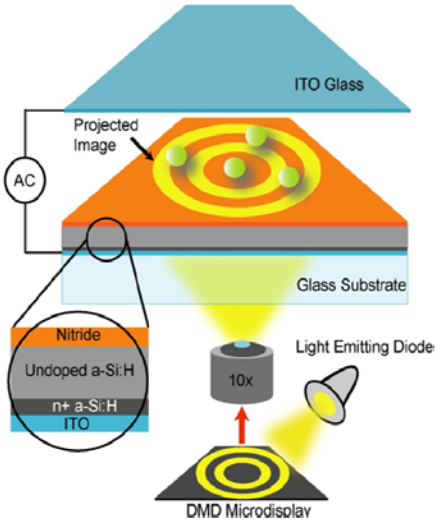

Fig. 1. OET use the selective illumination of a photoconductive layer to create 'virtual electrodes' for dielectrophoresis. Parallel manipulation of cells can be realized using projected optical images. [1]

II. PRINCIPLE OF OPTOELECTRONIC TWEEZERS

Figure 1 shows the experimental setup of OET. The particle is suspended in a liquid chamber consists of a top indium-tin-oxide (ITO) electrode and a bottom photoconductive electrode made of amorphous silicon (~ 1 μm thick). The chamber is biased with an a.c. signal (typically ~ 10Vpp). The projected optical image creates virtual electrodes on the photoconductor (Fig. 1), producing non-uniform electric fields and enabling particle manipulation via DEP forces. The OET devices are inexpensive and attractive for disposable applications. The OET-based optical manipulation has two operational modes, positive OET and negative OET, as a result of the DEP forces induced for actuation. Particles can be attracted by or repelled from the illuminated area, depending on the a.c. electric field frequency and the particle's internal and surface dielectric properties. Figure 2 illustrates the electric field distribution for a ring trap with negative OET force. The particle is effectively confined by the light cage. We have performed a detailed

characterization of the OET trap, and showed that a trap stiffness of 8x10-7 N/m is achieved at very low optical power (8.3 μW) [15]. While the trap stiffness is comparable to that produced by optical tweezers, the light intensity of OET is three orders of magnitude lower. The low-power requirement enables us to use a spatial light modulator to simultaneously address a large number of traps. Using a digital micromirror device (DMD) projector, we have successfully demonstrated 15,000 individually addressable traps over an area of 1 mm x 1mm [1].

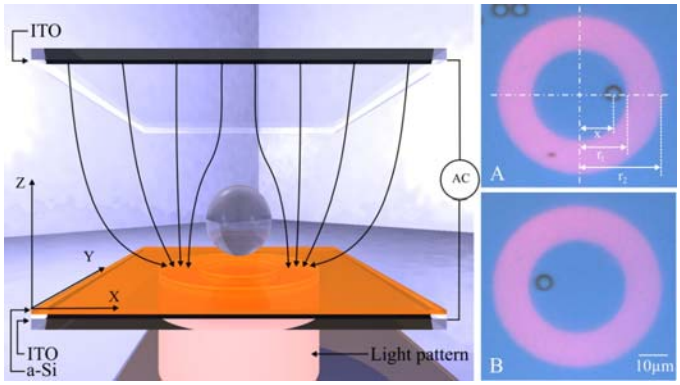

Fig. 2. An OET chamber consists of a liquid layer containing the beads sandwiched between two ITO-covered glass plates, one of which has a-Si covering it. When the stage is moved to the right (A) and then left (B), the particle is pushed in that direction. [15]

III. Cell Manipulation in Highly Conductive Physiological Buffer Solution

Phototransistor based optoelectronic tweezers are a new micromanipulation technique that allows the movement of cells by dielectrophoresis in a physiological buffer solution [11]. OET was first demonstrated with amorphous silicon as the photoconductive layer, however this limits the range of conductivities that can be used. Although cells have been manipulated by suspending them in an isotonic sugar solution of low conductivity, it is desirable to keep them suspended in physiological buffer solution to increase cell viability and lengthen the time cell can be kept healthy whilst being experimented on. To achieve this we have developed a phototransistor-based OET (Ph-OET) device [11]. The photo-transistor provides a higher photoconductivity than amorphous silicon and is designed to allow trapping in physiological buffer solution that has conductivity 1 S/m. We have performed detailed characterization of the Ph-OET trap and found that the minimum trap size for a HeLa cell is 24 μm in diameter which can move cells at 20μm/s, giving a trap stiffness of 8 x10-7 N/m [5].

IV. Trapping of Nanowires / Nanoparticles and NanoPen

Recently, we have successfully trapped individual semiconductor as well as metallic nanowires with diameters of 100 nm and length of a few microns [12]. Nanowires have high aspect ratio, and their polarizability along the length direction is about three orders of magnitude larger than the spherical nanoparticles with the same diameter, resulting in large OET force. The nanowires experience positive OET force. We have successfully trapped and transported single nanowires using a 100-μW HeNe laser source. The low optical power avoids damaging of the nanowires often seen in trapping by optical tweezers. It is interesting to note that even with an optical beam size of 10 μm, we are able to separate nanowires spaced by less than 1 μm by moving the light spot. A maximum speed of 135μm/sec is obtained at 20 Vpp.

We have also reported on trapping of single and multiple spherical gold nanoparticles with 60 to 250 nm diameters using OET [13]. Thanks to the low optical intensities required for stable trapping (20 μW over 1.7 μm spot), we estimate the temperature increase in OET-trapped nanoparticles due to absorption to be $\Delta T < 0.1°C$, making OET-trapped nanoparticles suitable for biological imaging and sensing applications. In addition, we observe translational velocities of 68 μm/s and demonstrate trapping of both single and multiple nanoparticles in a single trap.

Another new exciting new development is NanoPen, a novel technique for light-actuated patterning of nanoparticles. The NanoPen mechanism consists of two distinct forces: a collection force which is responsible for collecting the particles in the light spot and an immobilization force which attracts the particles and immobilizes them on the OET surface. The collection force is a combination of DEP force, and a flow-based mechanism called light-actuated AC electroosmosis (LACE) [8, 16], which collects the particles over a longer range, concentrating them in a flow dead zone in the center of the light pattern. The immobilization force which is responsible for attracting the particles to the surface is mainly dominated by the DEP force but is also affected by electrophoresis forces due to the particles surface charges. Figure 3 shows NanoPen immobilization and patterning of a mixture of 60 and 90 nm gold nanoparticles dispersed in a 4 mS/m solution of KCl and DI water. A linewidth of ~3 μm was achieved for a scanning speed of ~5 μm/s. One of the applications of NanoPen patterned metallic nanoparticle structures is in the area of surface-enhanced Raman spectroscopy (SERS) sensing. To demonstrate this capability, we dried a solution of Rhodamine 6G (R6G) dye on the surface of the patterned structure in Figure 3. Strong Raman signal was detected at hot spots with high density of gold nanoparticles.

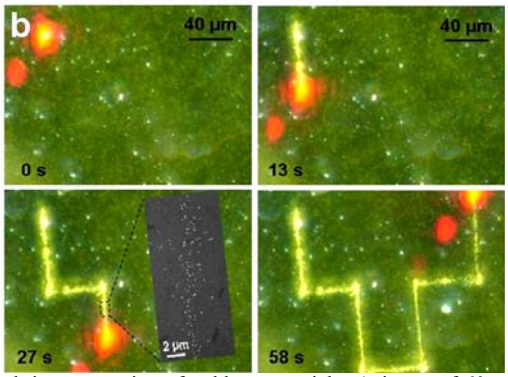

Fig. 3. Real-time patterning of gold nanoparticles (mixture of 60 nm and 90 nm in diameter) using a manually controlled laser spot. The field gradients formed in the vicinity of the optically defined virtual electrodes interact with

the nanoparticles, trapping them in the potential well. The particles are strongly attracted to the surface by the immobilization force consisting of DEP and electrophoresis forces. [14]

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REFERENCES

[1] G. Eason, B. Noble, and I. N. Sneddon, “On certain integrals of Lipschitz-Hankel type involving products of Bessel functions,” Phil. Trans. Roy. Soc. London, vol. A247, pp. 529–551, April 1955. *(references)*

[2] [1] P. Y. Chiou, A. T. Ohta, and M. C. Wu, "Massively parallel manipulation of single cells and microparticles using optical images," Nature, vol. 436, pp. 370-372, Jul 21 2005.

[3] [2] A. T. Ohta, C. Pei-Yu, H. L. Phan, S. W. Sherwood, J. M. Yang, A. N. K. Lau, H. Y. Hsu, A. Jamshidi, and M. C. Wu, "Optically controlled cell discrimination and trapping using optoelectronic tweezers," IEEE Journal of Selected Topics in Quantum Electronics, vol. 13, pp. 235-43, 2007.

[4] [3] A. T. Ohta, P. Y. Chiou, T. H. Han, J. C. Liao, U. Bhardwaj, E. R. B. McCabe, F. Yu, R. Sun, and M. C. Wu, "Dynamic Cell and Microparticle Control via Optoelectronic Tweezers," Microelectromechanical Systems, Journal of, vol. 16, pp. 491-499, 2007.

[5] [4] P. Y. Chiou, W. Wilson, J. C. Liao, and M. C. Wu, "Cell addressing and trapping using novel optoelectronic tweezers," in 17th IEEE International Conference on Micro Electro Mechanical Systems. Maastricht MEMS 2004 Technical Digest Maastricht, Netherlands, 2004, pp. 21-4.

[6] [5] S. L. Neale, A. T. Ohta, H.-Y. Hsu, J. K. Valley, A. Jamshidi, and M. C. Wu, "Force versus position profiles of HeLa cells trapped in phototransistor-based optoelectronic tweezers," in SPIE Photonics West, 2009.

[7] [6] Y.-S. Lu, Y.-P. Huang, J. A. Yeh, C. Lee, and Y.-H. Chang, "Controllability of non-contact cell manipulation by image dielectrophoresis (iDEP)," Optical and Quantum Electronics, vol. 37, pp. 1385-95, 2005.

[8] [7] W.-Y. Lin, Y.-H. Lin, and G.-B. Lee, "Contiunous Micro-Particle Separation Using Optically-Induced Dielectrophoretic Forces," in IEEE International Conference on Micro Electro Mechanical Systems (MEMS), Sorrento, Italy, 2009., 2009.

[9] [8] P. Y. Chiou, A. T. Ohta, A. Jamshidi, H. Y. Hsu, and M. C. Wu, "Light-Actuated AC Electroosmosis for Nanoparticle Manipulation," Journal of Microelectromechanical Systems, vol. 17, pp. 525-531, 2008.

[10] [9] H. Hwang and J. K. Park, "Rapid and selective concentration of microparticles in an optoelectrofluidic platform," Lab on a Chip, vol. 9, pp. 199-206, 2009.

[11] [10] J. K. Valley, H.-Y. Hsu, S. Neale, A. T. Ohta, A. Jamshidi, and M. C. Wu, "Assessment of Single Cell Viability Following Light-Induced Electroporation through Use of on-Chip Microfluidics " in IEEE International Conference on Micro Electro Mechanical Systems (MEMS), Sorrento, Italy, 2009., 2009.

[12] [11] H. Y. Hsu, A. T. Ohta, P. Y. Chiou, A. Jamshidi, and M. C. Wu, "Phototransistor-based optoelectronic tweezers for cell manipulation in highly conductive solution," in 2007 14th International Conference on Solid-State Sensors, Actuators and Microsystems (TRANSDUCERS '07 & Eurosensors XXI) Lyon, France, 2007.

[13] [12] A. Jamshidi, P. J. Pauzauskie, P. J. Schuck, A. T. Ohta, P.-Y. Chiou, J. Chou, P. Yang, and M. C. Wu, "Dynamic manipulation and separation of individual semiconducting and metallic nanowires," Nature Photonics, vol. 2, pp. 86-89, 2008.

[14] [13] A. Jamshidi, H.-Y. Hsu, J. K. Valley, A. T. Ohta, S. Neale, and M. C. Wu, "Metallic Nanoparticle Manipulation Using Optoelectronic Tweezers," in IEEE International Conference on Micro Electro Mechanical Systems (MEMS), Sorrento, Italy, 2009.

[15] [14] A. Jamshidi, P. J. Schuck, P. J. Pauzauskie, J. K. Valley, H.-Y. Hsu, A. T. Ohta, S. Neale, and M. C. Wu, "NanoPen: Light-actuated Patterning of Nanoparticles," in IEEE LEOS Winter Topicals Innsbruck, Austria, 2009.

[16] [15] S. L. Neale and M. C. Wu, "Trap stiffness in negative Optoelectronic Tweezers (OET)," in Conference on Lasers and Electro-Optics (CLEO), 2008, p. Paper CThLL6.

[17] [16] J. K. Valley, A. Jamshidi, A. T. Ohta, H. Y. Hsu, and M. C. Wu, "Operational Regimes and Physics Present in Optoelectronic Tweezers," Journal of Microelectromechanical Systems, vol. 17, pp. 342-350, 2008.

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