Optoelectronic tweezers

Using projected light patterns to form virtual electrodes on a photosensitive substrate, optoelectronic tweezers are able to grab and move micro- and nanoscale objects at will, facilitating applications far beyond biology and colloidal science.

Ming C. Wu

Optoelectronic tweezers (OETs) are a new optical manipulation concept that use projected optical images to grab and corral tiny particles with sizes ranging from hundreds of micrometres to tens of nanometres[1,2]. As the name suggests, OETs make use of both light and an electric bias to sculpt a potential landscape on a photosensitive substrate. Light first creates 'virtual electrodes' on the substrate, as shown in Fig. 1. These virtual electrodes locally concentrate the electric field in a manner similar to that of a lightning rod. The resulting non-uniform electric field exerts forces on dielectric particles through an interaction with the induced dipole moments in both the particles and the surrounding media — a phenomenon known as dielectrophoresis (DEP)[3]. If the particle is less polarizable than the surrounding liquid, as is the case for polystyrene beads in water, it will be repelled by the light pattern. This 'light wall' therefore confines the particle while still allowing exogenous chemicals to flow freely around it.

OETs combine the advantages of two well-known particle manipulation techniques: optical tweezers and electrode-based DEP. Optical tweezers, invented by Arthur Ashkin at Bell Laboratories 25 years ago, are used to trap small objects at the brightest point of a tightly focused laser beam[4]. This effect is also known as the optical gradient force because the force experienced by the object is proportional to the gradient of optical intensity. Optical tweezers are widely used in laboratories around the world for studying molecular motors and colloidal science. Holographic optical tweezers use many independently controlled tweezers to create artificial assemblies of cells, colloids and other objects in full three-dimensional space[5]. The main drawback of optical tweezers is that forming stable traps requires high optical intensities (>10^5 W cm^{-2}), which can damage fragile objects such as biological cells or nanoparticles. DEP, also known as the electrical gradient force, is the electrical analogue of optical tweezers. Traditionally, DEP is produced by fixed metal electrodes. Dynamic manipulation requires individually addressable two-dimensional electrode arrays. This has been realized by complementary metal–oxide–semiconductor (CMOS) integrated circuits, but at the expense of higher chip cost[6]. The resolution of the trap is limited by the size of the physical electrode. The use of virtual electrodes in OETs achieves both dynamic optical addressability and large forces at low light intensities (~1 W cm^{-2}). Because OETs convert light to electrical carriers, a coherent light source is not required, unlike optical tweezers. In fact, simple commercial digital projectors are perfect programmable light sources for use in OETs.

OET devices are conceptually similar to solar cells. Instead of generating photocurrents, the photogenerated carriers increase the conductance locally near the illuminated area, thus forming virtual electrodes. Amorphous silicon, which is widely used in solar cells and flat-panel displays, is an ideal photoconductor for OETs because it exhibits high resistance in the absence of light and high conductance under illumination. OETs can potentially be produced at low cost and in high volume using foundries for thin-film solar cells and flat-panel displays. The annual production of these amorphous silicon products is sufficient to cover an area of 100 km^2 at a cost of less than US$100 m^{-2}. OET devices the size of glass slides should therefore cost no more than a fraction of a dollar, making them attractive for disposable applications. Researchers have also explored OETs based on P3HT:PCBM, one of the promising organic solar-cell materials[7]. P3HT:PCBM can be spin-coated on glass, potentially at very low cost. The polymer layer is protected by a thermally evaporated LiF thin film to prevent damage from exposure to water and oxygen. OETs have also been constructed from organic photoconductive materials such as titanium oxide phthalocyanine[8], which is widely used in the xerographic photoreceptors of

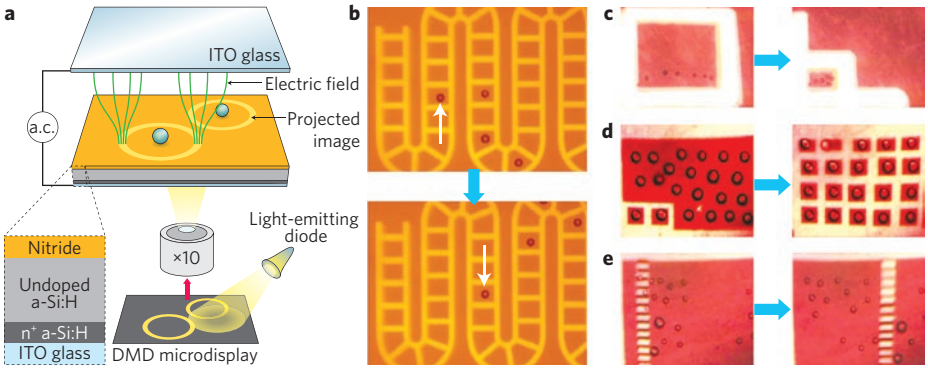

Figure 1 | Optoelectronic tweezers. **a**, Experimental set-up[1] and internal structure. Liquid-containing particles are sandwiched between a transparent electrode and a photoconductive (amorphous silicon, a-Si:H) electrode. Light patterns from a digital projector are imaged by an objective (×10) onto the device. The image, together with an a.c. electrical bias, generates 'virtual electrodes' that in turn create dielectrophoretic traps in the illuminated areas. DMD, digital micromirror device; ITO, indium tin oxide. **b**, An optical conveyer belt carrying 20-μm-diameter polystyrene particles. **c**, A shrinking light cage concentrates particles into a corner. **d**, A 4 × 5 array of individually addressable traps. **e**, A moving light comb pushes large 45-μm-diameter particles away, leaving small 20-μm-diameter particles behind. Figure reproduced with permission from: **a**, ref. 1, © 2005 NPG; **c**–**e**, ref. 10, ©2007 IEEE.

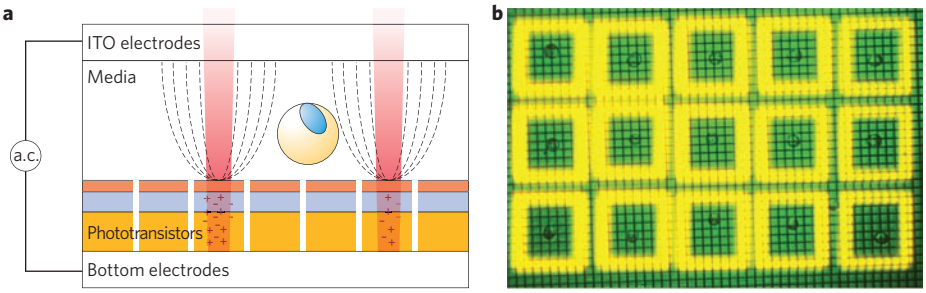

Figure 2 | Phototransistor-based optoelectronic tweezers. **a**, Cross-sectional view, illustrating the operating principle. The photoconductivity of silicon phototransistor is 500 times that of amorphous silicon, allowing it to operate in highly conductive liquids such as cell-culture media, which have conductivities of around 1.4 S m^{-1}. **b**, A 3 × 5 array of K562 cells captured by phototransistor-based OETs. The cells can be cultured while trapped to study the heterogeneity of their doubling rate. Figure reproduced from: **a**, ref. 18, © 2011 RSC; **b**, ref. 19, © 2011 IEEE.

photocopiers and laser printers[9]. Although long-term reliability is still a potential issue, the organic photovoltaic industry is sure to make continued improvements to the material technology.

Figure 1a shows a typical experimental set-up of OETs[1]. First, light patterns from a digital projector (or any type of spatial light modulator) are projected onto the OETs. The image, in conjunction with an externally applied electrical bias, creates localized DEP traps in the illuminated areas. On-demand parallel DEP trap generation is achieved by altering the optical pattern[10]. Figure 1b shows an optical conveyer belt transporting 20-μm-diameter beads. A shrinking light cage corrals randomly distributed particles towards a desired location (Fig. 1c). Alternatively, an individually addressable array can be formed by projecting a light cage around each particle, which can then be arranged into a regular array (Fig. 1d). The light pattern can also be used to probe the dielectric property of the particles. For example, a moving light comb separates the particles according to size (Fig. 1e). Particles larger than the comb spacing are carried away by the sweeping comb, leaving smaller particles behind. Through this method, it is possible to separate particles whose diameters differ by less than 1 μm.

OETs have seen a multitude of variants emerge over the years. Standard OETs (Fig. 1a) consist of a liquid chamber (containing the particles of interest) sandwiched between a photosensitive electrode and a transparent indium tin oxide electrode, across which an a.c. voltage bias is applied. Several variations of this construction have been reported. One extension uses virtual electrodes on both the top and bottom substrates for stronger particle confinement[11]. Researchers have also reported single-sided OETs without the top indium tin oxide electrode, in which the bias is applied either laterally on interdigitated electrodes[12] or across the entire photoconductive film — devices known as floating-electrode OETs[13]. Single-sided OETs are more easily integrated with other microfluidic devices than standard OETs[14]. The virtual electrodes in floating-electrode OETs can be activated at light intensities as low as 0.4 mW cm^{-2}, which is almost three orders of magnitude lower than for normal OETs. This allows floating-electrode OETs to be actuated by putting the device directly on top of a cell-phone screen. Furthermore, floating-electrode OETs are capable of manipulating both particles and liquid droplets in an oil environment[13].

One attractive application of OETs is for organizing and assembling nanowires and nanoparticles into arrays of controllable size and density[2,15]. Over the past decade, chemists and material scientists have developed 'bottom-up' techniques for synthesizing nanowires and nanoparticles from a wide variety of materials. The heterogeneous integration of such nanoscale building blocks could lead to new functional materials and devices. However, trapping a nanoparticle is challenging because the gradient forces involved (both optical and electrical) are proportional to the nanoparticle's volume. In addition, trapping forces at the nanoscale can be overcome by Brownian motion. Fortunately, researchers have found that the DEP force on a nanowire in OETs is significantly larger than expected because of the large electrical polarizability along the nanowire's length. This large DEP force makes it possible for OETs to trap individual nanowires with diameters as small as 20 nm. Simultaneous addressing of a 5 × 5 array of individual nanowires has also been demonstrated. OETs have also been used to trap single gold nanoparticles, quantum dots and single carbon nanotubes[16].

OETs also have interesting applications in the biosciences. Specifically, they can provide a quantitative assessment of embryos for *in vitro* fertilization[17]. Selection of optimal-quality embryos is critical for achieving successful live birth outcomes. Currently, embryos are chosen based on the subjective assessment of morphologic developmental maturity. A non-invasive means of quantitatively measuring an embryo's developmental maturity would reduce the variability introduced by today's methods. OETs have been used to exploit the scaling electrical properties of pre-transfer embryos to quantitatively discern embryo developmental maturity. Researchers have shown that an embryo's response to OETs is highly correlated with its developmental stage. This technique therefore allows one to select, in sequence and under blinded conditions, the most developmentally mature embryos among a mixed cohort of morphologically indistinguishable embryos cultured in either optimal or suboptimal culture media. OETs therefore provide a non-invasive, quantitative and reproducible means of selecting embryos for applications such as *in vitro* fertilization transfer and embryonic stem-cell harvest.

Long-term biological experiments require cells to be kept in culture media or physiological buffers, which intrinsically exhibit high electrical conductivity (1.4 S m^{-1}). However, amorphous silicon-based OETs can only operate in low-conductivity media (<0.1 S m^{-1}) because of their finite photoconductivity[12]. Thus, to manipulate mammalian cells in conventional OETs, the salts in cell culture media must be replaced by osmotically equivalent amounts of non-electrolytes[12]. Although this provides short-term sustainment, cells begin to lose normal functions such as proliferation and growth after a few hours. This challenge was recently overcome by replacing the amorphous silicon photoconductor with a phototransistor, which exhibits up to 500 times higher photoconductivity[18,19]. Phototransistor-based OETs enable cell manipulation in culture media (Fig. 2). Efficient cell trapping of live HeLa and Jurkat cells in phosphate-buffered saline and Dulbecco's modified Eagle's medium has been demonstrated using a digital light projector.

Although this Commentary has primarily discussed the light-induced DEP mechanism, several other electrokinetic and hydrodynamic effects are also present in OETs. Light-induced fluidic flow resulting from a.c. electro-osmosis and

electrothermal effects may also occur, but these can be minimized by keeping the voltage bias frequency high (>10 kHz) and the optical intensity low (<100 W cm^{-2})[20]. Alternatively, one can take advantage of light-controlled fluidic flow to concentrate and pattern nanoscale particles and molecular-scale objects such as DNA[21–24]. Through a slight modification of standard OETs, light-patterned virtual electrodes can also be used to transport, separate, combine and mix liquid droplets through an effect called optoelectrowetting[25]. Using a unified optoelectrowetting/OET platform, particle concentration within (and subsequent splitting of) a droplet has been performed to increase the particle concentration in the droplet[26].

OETs are new versatile tools that allow direct optical addressing of micro- and nanoscale objects using projected optical images on photosensitive substrates. As this field moves forward, the unique capabilities of OET are likely to facilitate new and exciting investigations in biology, colloidal science and beyond. ❐

Ming C. Wu is at the Department of Electrical Engineering and Computer Sciences and Berkeley Sensor and Actuator Center, University of California, Berkeley, California 94720, USA.
e-mail: wu@eecs.berkeley.edu

References

1. Chiou, P. Y., Ohta, A. T. & Wu, M. C. *Nature* **436,** 370–372 (2005).
2. Jamshidi, A. *et al. Nature Photon.* **2,** 86–89 (2008).
3. Pohl, H. A. *Dielectrophoresis: The Behavior of Neutral Matter in Nonuniform Electric Fields* (Cambridge Univ., 1978).
4. Ashkin, A., Dziedzic, J. M., Bjorkholm, J. E. & Chu, S. *Opt. Lett.* **11,** 288–290 (1986).
5. Grier, D. G. *Nature* **424,** 810–816 (2003).
6. Manaresi, N. *et al. IEEE J. Solid-St. Circ.* **38,** 2297–2305 (2003).
7. Wang, W. *et al. Opt. Express* **17,** 17603–17613 (2009).
8. Yang, S.-M. *et al. Opt. Lett.* **35,** 1959–1961 (2010).
9. Law, K. Y. *Chem. Rev.* **93,** 449–486 (1993).
10. Ohta, A. T. *et al. J. Microelectromech. S.* **16,** 491–499 (2007).
11. Hwang, H. *et al. Appl. Phys. Lett.* **92,** 024108 (2008).
12. Ohta, A. T. *et al. IEEE J. Sel. Top. Quant.* **13,** 235–243 (2007).
13. Park, S. *et al. Appl. Phys. Lett.* **92,** 151101 (2008).
14. Shah, G. J., Ohta, A. T., Chiou, E. P.-Y., Wu, M. C. & Kim, C.-J. *Lab Chip* **9,** 1732–1739 (2009).
15. Ohta, A. T., Neale, S. L., Hsu, H. Y., Valley, J. K. & Wu, M. C. *Proc. IEEE/LEOS Int. Conf. Opt. MEMs Nanophoton.* **2008,** 7–8 (2008).
16. Pauzauskie, P. J., Jamshidi, A., Valley, J. K., Satcher, J. H. Jr & Wu, M. C. *Appl. Phys. Lett.* **95,** 113104 (2009).
17. Valley, J. K. *et al. PLoS ONE* **5,** e10160 (2010).
18. Hsu, H.-Y. *et al. Lab Chip* **10,** 165–172 (2010).
19. Hsu, H. Y. *et al. Proc. IEEE 24th Int. Conf. MEMS* 63–66 (2011).
20. Valley, J. K., Jamshidi, A., Ohta, A. T., Hsu, H. Y. & Wu, M. C. *J. Microelectromech. S.* **17,** 342–350 (2008).
21. Chiou, P. Y., Ohta, A. T., Jamshidi, A., Hsu, H. Y. & Wu, M. C. *J. Microelectromech. S.* **17,** 525–531 (2008).
22. Williams, S. J., Kumar, A., Green, N. G. & Wereley, S. T. *Nanoscale* **1,** 133–137 (2009).
23. Hwang, H. & Park, J.-K. *Lab Chip* **9,** 199–206 (2009).
24. Jamshidi, A. *et al. Nano Lett.* **9,** 2921–2925 (2009).
25. Chiou, P. Y., Moon, H., Toshiyoshi, H., Kim, C.-J. & Wu, M. C. *Sensor. Actuat. A* **104,** 222–228 (2003).
26. Valley, J. K., NingPei, S., Jamshidi, A., Hsu, H.-Y. & Wu, M. C. *Lab Chip* **11,** 1292–1297 (2011).