Fully Automatic Wafer-scale Micro/Nano Manipulation Based on Optically Induced Dielectrophoresis

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Abstract. Optically induced dielectrophoresis (ODEP) has been proved experimentally as a powerful method for efficiently manipulating some micro-scale, or even nano-scale objects. However, few ODEP platforms have been demonstrated towards the fully automatic wafer-scale manipulation and rapid fabrication of micro and nano sensors and devices. That would be of great significance to the application and industrialization of micro and nano materials. In this paper, an innovative ODEP platform for reconfigurable and automatic micro/nano-scale material manipulation is presented by combining microactuation and microvision analysis with ODEP technology. The ODEP chip consists of a typical photoconductive layer of amorphous silicon, which generates a nonuniform electric field at the light-illuminated region to induce dielectrophoretic (DEP) force for manipulating particles within the chip. A high resolution 3D motorized stage enables an accurate and rapid movement of the chip in wafer-scale. The microvision analysis program automatically recognizes the positions and sizes of randomly distributed particles and creates direct image patterns to manipulate the selected particles to form a predetermined pattern in predesired position. The programmed dynamic reconfigurable optical patterns provide increased functionality and versatility in particle manipulation. The patterning of polystyrene beads with different sizes is accomplished. This platform may be promising for rapid and wafer-scale fabrication of micro and nano sensors and devices, high-throughput bio-sample pretreatment and other applications requiring massively parallel manipulation.

Introduction

The application of micro/nano-scale materials, including particles, beads, wires/rods and bio-entities in a variety of fields continues to steadily increase and has made substantial impact. To apply micro/nano-scale materials to many practical applications, it is essential to efficiently manipulate and arrange them at desired sites with predetermined patterns and quantities. Various kinds of forces were applied to manipulate micro/nano-scale materials. Although mechanical structures can be used to grip microparticles [1], however it is difficult and costly to scale mechanical devices for the parallel manipulation of single particles. Conversely, fluid drag can transport many cells [2], but it is extremely difficult to achieve single-cell manipulation using fluidic manipulation. Optical tweezers [3] can manipulate a single particle, but it suffers from a high optical power requirement. Dielectrophoresis (DEP) [4] can also be used to trap particles, but it requires a static pattern of metal electrodes, which cannot be dynamically reconfigurable. A novel manipulation tool called optoelectronic tweezer (OET) was reported by P. Y. Chiou et al., in 2005 [5], which enabled massively parallel manipulation of micro-scale objects. The OET uses a photoconductive thin film to induce a nonuniform electric field with optical illumination, generating an optically induced dielectrophoretic (ODEP) force on particles in the OET devices. The OET manipulation has been
demonstrated on a variety of microparticles including polystyrene beads [6], blood cells [7], DNA [8], silicon nanowires [9], carbon nanotubes [10] and gold nanoparticles [11]. The ODEP technology may be a promising approach for cost-effective and high-throughput manipulation and assembly of micro/nano-scale materials. However, few ODEP platforms have been demonstrated towards the rapid and wafer-scale fabrication of micro and nano sensors and devices. That would be of great significance to the application and industrialization of micro and nano materials.

In this paper, we present an integrated ODEP platform for fully automatic manipulation of micro/nano-scale materials by combining microactuation and microvision analysis with ODEP technology. A high-resolution X-Y-Z motorized stage is used to produce an accurate and rapid movement of the OET device in wafer scale. A microvision analysis program is developed to automatically recognize the positions and sizes of randomly distributed particles and create direct image patterns to manipulate and assemble the selected particles to form a predetermined pattern in a specific position. Manipulation of polystyrene beads with different sizes is performed.

**System Design and Experimental Setup**

**ODEP Fundamentals**  
Fig. 1 shows the schematic illustration of the OET device, which consists of an upper transparent conductive indium-tin oxide (ITO)-coated glass and a bottom photosensitive surface, which sandwich a layer of liquid solution containing the micro/nano-scale samples of interest. The bottom surface is fabricated on an ITO glass substrate and is comprised of a pattern-less photoconductive material layer of hydrogenated amorphous silicon (a:Si-H) with the thickness of 1µm. A 60µm spacer is used to maintain the gap between the upper and the lower surfaces. An AC bias across the top and bottom ITO layers is applied to power the device.

The OET device addresses optically induced DEP by utilizing the photoconductive properties of the a:Si-H layer. a:Si-H has very high electrical impedance originally. Under no optical illumination, most of the applied voltage drops across the a:Si-H layer, resulting in a very low electric field in the liquid layer. Optical illumination onto the a:Si-H surface generates electron-hole pairs to increase the conductivity of the bottom layer by several orders of magnitude. As a result, a “virtual electrode” is created in the illuminated area. Thus, most of the voltage drop is switched to the liquid layer, creating an inhomogeneous electric field across inside. In the presence of the nonuniform electric field, DEP force is induced for particle manipulation. Particles can be attracted by or repelled from the illuminated area, depending on the electric field frequency and the particle’s dielectric properties.

**Experimental Setup**  
Fig. 2 shows the schematic diagram of the integrated ODEP manipulation system. A mixture of polystyrene beads with different sizes (Polysciences Inc., USA) is randomly suspended in deionized water (DI-water) with conductivity of 9mS/m. The movement of the particles is captured by a charge-coupled device (CCD, Daheng Image, China) through a microscope (Zoom 160, OPTEM, USA) and sent to a computer for image analysis. A self-developed Visual C++6.0 program automatically recognizes the positions and sizes of the randomly distributed particles and creates direct image patterns to trap and transport the selected particles. These optical patterns are then transferred to a LCD projector (VPL-F400X, Sony, Japan) with a 1024×768 resolution. The
output of the projector is collected, collimated and directed into an objective lens (50X, Nikon, Japan), projecting an image onto the OET device. The resulting resolution of the projected optical image on the OET device is approximately 5µm. The OET device is situated on a high-resolution 3D motorized stage, which has a XY travel range of 100mm x 100mm. If the final position of the particles is out of the field-of-view of the microscope, the program calculates the trajectories of the particles to reach their final positions, and optimizes the corresponding movement of both the 3D stage and the optical patterns to ensure the particles reach their predetermined configurations and positions. A function generator (AFG3022B, Tektronix, USA) is used to apply an AC voltage to the top and bottom transparent ITO surface of OET device to generate the DEP force.

Results and Discussions

Particle Recognition Canny’s algorithm is used to implement particle edge detection. Fig. 3(a) shows an original color image of randomly distributed particles of four different sizes, 5µm, 10µm, 20µm and 45µm. The image brightness at the particle edge changes sharply. This change is measured by calculating brightness gradient and gradient direction. The point at which gradient is local maximum along gradient direction is set to be the edge point. Then, a horizontal or vertical line is used to scan each particle. The number of pixels between two intersecting points of the line and the particle edge is counted to determine the size of each particle. The maxima of pixels indicate the diameter of the particle. And the x and y position data of the intersecting points are averaged to determined the center position of each particle. As shown in Fig. 3(b), white ring patterns generated by the microvision analysis program is used to mark the recognized particles.

Patterning of Micro Beads We have implemented the parallel trapping, transporting and patterning of 10µm and 45µm polystyrene beads into a triangular shape. Fig. 4(a) shows the simulated electric field distribution in the liquid layer at three different heights above the photoconductive surface. The projected optical pattern has a ring-shape with an inner radius of 25µm and a width of 5µm. The applied AC voltage is 20Vpk-pk at a frequency of 30kHz. The electric field strength near the light-patterned region is stronger than that at the center of the ring, and the lower the height, the stronger the electric field strength. That makes this pattern ideal for particle trapping. Fig. 4(b) shows
the maximum DEP force experienced by 10µm and 45µm beads, respectively. In radial direction, the DEP force reaches the maximum at the ring edge, approximately 2pN and 5.5pN for 10µm and 45µm beads, respectively. Both the 10µm and 45µm beads experience negative DEP force, which pushes the particles in the direction toward the center. While the optical ring moves, the trapped particle moves together with the optical ring in the same direction.

By designing the trajectory of optical patterns through self-developed program, the beads can be automatically patterned in any sequence to form any configuration. Initially, as shown in Fig. 5(a), beads are distributed randomly in the DI-water solution. Once the target particles are recognized, program generates the corresponding optical ring patterns to capture each particle (Fig. 5(b)) and calculates the trace to the predesired position for each particle. These optical patterns are stored as another image file and are focused onto the photoconductive layer by the objective lens through the projector. The trapped particles are transported by moving the optical ring patterns, and reach the big and small line shape (Fig. 5(c)). Then two 45µm and one 10µm beads in the middle of the line are held statically in the positions, and other three beads are transported upward simultaneously (Fig. 5(d) and (e)). Finally, a triangular configuration with three 45µm beads at the vertices and three 10µm beads at the midpoints of three sides is formed (Fig. 5(f)). The unwanted particles surrounding the triangular are pushed away by a continuously enlarging optical ring pattern under the action of negative DEP force, as shown in Fig. 5(g) and (h). Fig. 5(i) is the final configuration of the particles after optical light patterns are off. Particle movement is observed to be approximately 25µm/sec.
Conclusions

We have successfully demonstrated a fully automatic, reconfigurable, and real-time optically driven platform that can automatically recognize, capture, and transport particles to form a predetermined pattern in a specific position. The major advantages of our platform over other existing ODEP systems are that, the microvision-based close-loop control makes the platform a fully automatic system; by using a 3D stage with a XY travel range of 100mm × 100mm, the platform is suitable for wafer (4”) applications; Using the self-developed microvision analysis program, the platform can realize combined multiple manipulation functions with high flexibility and reconfigurability. The developed platform shows a great potential for rapid and wafer-scale fabrication of micro and nano sensors and devices, high-throughput bio-sample pretreatment and other applications requiring massively parallel manipulation.

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