Three-Dimensional Dielectrophoresis Device with Integrated Actuating and Impedance Sensing

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Abstract

Lab on a chip technology is the next generation of laboratory processes, which will allow the reduction in size of complex experimental setups to the size of a thumb. The lab on a chip device we are reviewing utilizes electronic manipulation and detection of microorganisms through a combination of dielectrophoresis (DEP) and impedance sensing. The reviewed device utilizes printed PCB board as the basis for electronic manipulation of polystyrene microbeads in close agreement with CAD simulations. The experiments were successfully repeated using S. Cerevisiae yeast cells, proving the effectiveness of DEP for particle manipulation and the ability of impedance sensing to eliminate optical and chemical detection methods. We then propose the further development of this technology to the microscale, outlining a manufacturing procedure using MEMS techniques such as lithography and chemical etching to allow for large scale production of devices in a silicon wafer array.
**Introduction**

Many chemical, biological, and medical fields currently consist of an incomprehensible number of various tests, experiments and processes which can be characterized by their need for integration of complex protocols and use of complex equipment. Lab-on-a-Chip architecture seeks to scale down these individual processes to the size of conventional computer chips to simplify the experimental process by integrating all necessary functions into one local device. By integrating the functions of sensing, processing, and actuation into a compact package, the large and complex devices that plague macro-scale techniques can be eliminated, thus limiting human interaction with the experiment and simplifying the overall procedures. In addition to the reduction in procedural steps, experiments previously limited to a laboratory environment can be moved to new areas, allowing for on-site testing for many experiments which today require huge lead times. In the future, this may allow for on site analysis for tests such as DNA matching, food quality testing, and even water contamination, shortening the time required for these critical experiments.

Many of these Lab-on-a-Chip devices require the manipulation of chemicals or particles, requiring new and novel methods of controlling these items at the micro-scale. In particular, the manipulation of particles and cells is of particular interest, as they respond to unique properties absent in pure fluids and gasses. Dielectrophoresis (DEP) is a property which has been extensively exploited in the manipulation of cells, whereby a particle may respond to a changing electrical field due to an inherent polarization, whereby the particle may overall have a neutral charge, but charges may be separated within the particle. Positive DEP (pDEP) is the situation where a particle experiences a net force directed to locations with an increasing electric field intensity, whereby negative DEP (nDEP) is the method whereby a particles is attracted to decreasing field intensity. Problems arise with the use of pDEP and nDEP with the adhesion of particles to walls. Since the maxima of an electric field cannot be established away from the electrode, particles will tend to adhere to the electrode surface. With nDEP, in confined areas, particles may also be forced far enough away from an electrode to come in contact with walls. However nDEP provides a possibility for a particle to come into equilibrium with the force of gravity, allowing for possible levitation within a medium.
Within Lab-on-a-Chip devices, sensing methods typically associated with particle or cellular manipulation have been optical, involving fluorescent labeling in conjunction or separate from optical techniques. Unfortunately these methods negate the benefits of Lab-on-a-Chip architecture, usually requiring large instruments far above the size of the original chip. Additionally, there are typically an increased amount of steps necessary to prepare the sample to allow for optical detection.

Operation of stand alone devices such as Lab-on-a-Chip requires, at a minimum, a form of feedback to allow the system to self-operate and correct. In many existing Lab-on-a-Chip designs, the sensing system is entirely separate from the actuation apparatus. While this may not be a problem with the operation of the device, there is an increase in the fabrication required to create the entire system. Two separate systems must exist, each to accomplish only one task. It is desired that a minimum amount of fabrication be required, since this is the largest contributor to overall Lab-on-a-Chip cost.

We are proposing a device which addresses all of the previously stated problems, utilizing a form of nDEP to prevent particle adhesion with a sensing method other than optical means, which may be integrated with the existing actuation system. nDEP may be manipulated to create DEP “cages” which allow particles to be encased within a virtual tube created by various electrodes placed within a chamber. The particle detection system will no longer use optical means, but electrical impedance, as particles will interfere with electrical flow between the same electrodes creating the DEP cages. As described, the sensing method will be integrated into the electrodes responsible for actuation, reducing the necessary fabrication for the device. Combining these processes on the chip will enable the automation of sensing and actuation, essentially eliminating the need for human interaction within the system. Actuation can then be controlled by the sensing feedback, entirely contained within the chip architecture.

**Theory**

**DEP Background**

Dielectrophoresis (DEP) is a method of moving neutral particles within a non-uniform electric field. By placing electrodes in a particular asymmetric conformation, a gradient for an electric
field can be generated, which can create an electric dipole within neutral particles (in our case, a cell). Due to this phenomenon, cells can experience a net force directed towards increasing or decreasing field intensity, depending on the design of the chip. Extending this concept to 3D, a DEP cage can be created in order to trap particles, which is extremely useful in several areas of biotechnology, namely in electro-manipulation, focusing, characterization and detection.

The governing equation for a DEP-induced force upon a spherical particle is:

**Equation 1: DEP-Induced Force**

\[
F = 2\pi r^3 \epsilon_m \text{Re}[K] \nabla E^2
\]

where \( r \) is the radius, \( E \) is the nonuniform electric field, \( \epsilon_m \) is the permittivity of the liquid medium and \( \text{Re}[K] \) is the Clausius-Mossotti factor. Note that

**Equation 2: Clausius-Mossotti Factor**

\[
K = \frac{\epsilon_p^* - \epsilon_m^*}{\epsilon_p^* + 2\epsilon_m^*}
\]

where \( \epsilon_p \) is the permittivity of the particle.

The DEP-induced force can be negative or positive, giving it the capability to direct particles towards high electric field regions (positive DEP) or towards low electric fields (negative DEP). This phenomena is partially dependent on the linear relationship between the force and the polarizability relationship of the medium and particle (\( \text{Re}[K] \)). In other words, particles with a greater polarizability than the surrounding medium exhibit positive DEP relationships while particles with lower polarizability than the medium will react in the opposite manner. This ability allows us to concentrate similar particles or separate different particles.

In addition, the complex permittivity of the medium (\( \epsilon^* \)) is a function of the applied electric field frequency:

**Equation 3: Permittivity of the Medium**

\[
\epsilon^* = \epsilon - j \frac{\sigma}{\omega}
\]

where \( \sigma \) is the conductivity and \( \omega \) is the angle frequency of the electric field. Using Equation 3 and Equation 2, at low frequencies the Clausius-Mossotti factor can be approximated as
Equation 4: Clausius-Mossotti Factor at Low Frequencies

\[ K \approx \frac{\sigma_p - \sigma_m}{\sigma_p + 2\sigma_m} \]

At high frequencies the Clausius-Mossotti factor can be approximated as

Equation 5: Clausius-Mossotti Factor at High Frequencies

\[ K \approx \frac{\varepsilon_p - \varepsilon_m}{\varepsilon_p + 2\varepsilon_m} \]

At different frequencies, the polarization factor can be switched between positive and negative a value, allowing another control factor over positive of negative DEP force. These DEP concepts can be extended to 3-D, where electric fields varyingly extend into the vertical axis.

When considering vertical forces, the buoyancy force \( (F_B) \) of the particles must be accounted for as well:

Equation 6: Buoyancy Force

\[ F_B = \frac{4}{3} \pi r^3 \left( \rho_p - \rho_m \right) g \]

where \( r \) is the radius of the particle and \( \rho_p \) and \( \rho_m \) are the densities of the particle and medium, respectively.

The buoyancy force can act with or against the vertical DEP force, depending on the orientation. At a certain point between two electrodes, the vertical DEP force and buoyancy force will be in equilibrium, allowing particles to suspend in the solution above the surface.

Figure 1: Balancing Buoyancy and DEP Forces [5]

Balancing the DEP and buoyancy forces:
Equation 7: Balancing the DEP and Buoyancy Forces

\[ \text{Re}[K] \nabla E^2 = \frac{2(\rho_p - \rho_m)g}{3 \varepsilon_m} \]

This mechanism allows a device to concentrate particles in three dimensional spaces, as opposed to typical planar DEP devices.

![Figure 2: Concentration of Particles in DEP Cages [10]](image)

In addition, inertial and viscous forces in liquid must be taken into account. These forces varyingly scale based upon particle size. Since DEP forces are proportional to volume while viscous forces are proportional to surface dimensions, the ratio between DEP and viscous forces is:

**Equation 8: Ratio between DEP and Viscous Forces**

\[ \frac{F_{\text{DEP}}}{F_{\text{visc}}} \propto r \]

Due to this relationship, smaller particles will take longer to move than larger particles. In order to properly concentrate particles in a particular region, necessary wait times must be realized in order to account for slower particle dynamics.

In the proposed device, DEP has been utilized in three directions: creating a “focusing plane” in 2D and adding a vertical component for buoyancy in order to completely trap and focus cells.
**DEP Cages and Actuation**

The actuation of the electrodes on the bottom of the chip is responsible for DEP cage movement. DEP-induced forces will move particles towards the target electrode in order to increase the concentration of the matter being analyzed at that particular target electrode. The DEP cage is able to move towards the center of the chip by applying a counter-phase signal across the entire top plate of the chip while applying alternating in-phase and counter-phase signals to the bottom electrodes. The pattern on the bottom electrode, as seen in Figure 3, is an in-phase electrode bounded by out of phase electrodes, then moved towards the target electrode as in Figure 4.

![Figure 3: Formation and Actuation of DEP Cages [1]](image)

![Figure 4: Actuation of DEP Cages Towards Target Electrode [1]](image)
The time it takes to shift the DEP cage from one electrode to the next depends on the particle size. Upon an immediate cage shift, particles will remain still due to inertial and viscous forces, but will then move to the center of the shifted cage due to their vicinity within the attraction basin of the shifted cage. The time it takes for these particles to move to the center of the shifted cage determines the time period of actuation for the DEP cages.

Due to the aforementioned relationship between DEP and viscous forces, Equation 8, large particles move quicker to shifted DEP cages (for a particle with a diameter of 50μm travel time is approximately 2s) while smaller particles move slower (for a particle with a diameter of 3μm travel time is between 5-10s). The time period between shifting cages between electrodes must be chosen such that the smallest particles will not be left behind.

**Impedance Sensing**

To determine the concentration of particles in the DEP cages, impedance sensing is performed between the shifting of the DEP cages. This is done by connecting the measuring electrode to a transimpedance amplifier and connecting the rest of the electrodes to ground while still continuing to have the top plate connected to a counter-phase signal, seen in Figure 5.

During sensing, DEP cages are switched off. Since the time it takes for particles to fall to the bottom of the chamber (≈1s for the smallest particle) is much longer than the time it takes for impedance sensing to take place (≈10ms) particles will continue to levitate during sensing.
This transimpedance amplifier contains a capacitor with known capacitance, \( C_F \), and a Resistor with known Resistance, \( R_F \). The particles between the electrode and top plate will create a change in capacitance and resistance which can be sensed and correlated to the quantity of particles between the electrode and top plate. The transfer function for the sensing circuit was discovered through circuit analysis and is displayed in Equation 9 where \( V_o \) is the output voltage, \( V_i \) is the input voltage, \( R_F \) and \( C_F \) are the feedback resistance and capacitance, and \( R_M \) and \( C_M \) are the resistance and capacitance between the electrode and lid.

**Equation 9: Transfer Function for Sensing Circuit**

\[
\frac{V_o}{V_i}(jw) = -\frac{R_F}{R_M} \left(1 + jwR_M C_M \right) \left(1 + jwR_F C_F \right)
\]

At lower frequencies (\( w \ll 1/(R_M C_M) \) and \( w \ll 1/(R_F C_F) \)) the resistance effects will dominate the system and Equation 9 can be reduced to Equation 10.

**Equation 10: Sensing Equation at Low Frequencies**

\[
\frac{V_o}{V_i} = -\frac{R_F}{R_M}
\]

At higher frequencies (\( w \gg 1/(R_M C_M) \) and \( w \gg 1/(R_F C_F) \)) the capacitive effects will dominate the system and Equation 9 can be reduced to Equation 11.

**Equation 11: Sensing Equation at Higher Frequencies**

\[
\frac{V_o}{V_i} = -\frac{C_M}{C_F}
\]

Equation 4 illustrates that using a low frequency input stimulus will trap a particle if its conductivity is lower than the medium’s, leading to a decrease in conductivity between the electrode and the lid. If the same frequency is used for both activating the DEP cages and sensing then \( R_M \) will increase with the inclusion of trapped particles.

**Equation 12: Effect of Particles on Resistance at Low Frequencies**

\[
R_M^{wp} > R_M^{wop}
\]

where \( R_M^{wp} \) is the system with particles and \( R_M^{wop} \) is the system without particles. Using Equation 10 and 12, it can be seen that output voltage amplitude of the amplifier will decrease with trapped particles.
Equation 5 demonstrates that using a high frequency input stimulus will trap a particle if its permittivity is lower than the medium’s. If the same frequency is used for activating the DEP cages and sensing then:

**Equation 13: Effect of Particles on Capacitance at High Frequencies**

\[ C_{M}^{wp} < C_{M}^{wop} \]

Using Equation 11 and 13 it can also be seen that the output voltage amplitude will decrease with trapped particles.

A correlation can then be created between the amount of particles and the output voltage at both the low and high frequencies. This will allow for detection of particles by observing the output voltage of the system.

**Similar DEP Devices**

**CMOS Chip for Individual Cell Manipulation**

Using CMOS technology, this device was fabricated with 102,400 actuation electrodes, in a 320x320 array within a 8 x 8 mm² chip. Each electrode is 20 µm x 20 µm. This device allows the selection and manipulation of single cells. This device demonstrates the capability to manipulate up to 10,000 cells in parallel, which has potential in drug screening, cell separation and analysis. Instead of using capacitive sensing techniques, the authors propose an integrated method using optics.

*Figure 6: CMOS Chip [6]*
A Dielectrophoretic Chip with a 3-D Electric Field Gradient

In this device, the authors created an asymmetric 3D electric gradient through specially configured electrodes. Thick electrodes are integrated with vertical wall structures while thin planar electrodes are placed on the bottom layer substrate. This configuration achieves an enhanced vertical DEP force, allowing the device to run at lower voltages and temperatures.
MEMS Electrostatic Particle Transportation System

The authors here were able to construct an electrostatic device capable of transporting particles 5-10µm in diameter in air. They were able to demonstrate a relationship between particle transportation efficiency with insulator film thickness. Surface modification treatments were performed in order to reduce adhesive forces.

Fabrication Methods

The fabrication of this DEP Lab-on-a-Chip does not involve any MEMS construction techniques. (Scaling down this device with MEMS techniques is discussed further in the Recommendations section). The reviewed chip consists of a PCB board, gold electrodes, optic fiber spacers, a gasket and a transparent conductive lid. The base is a printed circuit board (PCB) that contains strips of gold electrodes that were attached during the fabrication of the board. The most common form for attaching electrodes to a PCB board is by silk screening the pattern onto a gold
clad board and then etching and removing the screened resist. The PCB board is separated from the conductive lid through the use of optic fibers, which determines the device’s height, while a gasket seals the microchamber. The lid is connected to the PCB device by using conductive glue. The device is shown in Figure 9 along with representations of DEP cages. Advantages for not using MEMS techniques include the possibility of having larger microchambers, decreased production costs and turnaround time.

Figure 9: Sketch of the Device [1]
Results

Parasitic Cages
One of the major problems that occur with this device is the formation of parasitic cages. These parasitic cages, represented as a dark spot between electrodes 3 and 4 in Figure 10a, are formed when a counter-phase signal is applied to one of the three electrodes, electrode 2 in Figure 10a, while an in-phase single is applied to the other two electrodes, electrodes 3 and 4 in Figure 10a. A parasitic nDEP cage will appear in between the two in-phase electrodes because this spot corresponds to an electric field minimum.

![Diagram of parasitic nDEP cage and shifted DEP cage](image)

Particles are injected into the microchamber in a random fashion, causing some to be trapped in parasitic cages after the device is activated because they are in the attraction basin of these cages. Particles in the parasitic cages can be recovered by shifting the DEP cage as seen in Figure 10b. Particles trapped in the original parasitic cage will now be attracted to the cage above electrode 3, but a new parasitic cage will form, attracting smaller particles from the original DEP cage due to their inherently slower movement through fluid.
Two methods were found to reduce the effect of parasitic cages. The first was to add an intermediate step while shifting the DEP cage, seen in Figure 11. During this step the particles are attracted to a DEP cage between the starting and ending electrodes. Although some particles are still trapped in a parasitic cage below the DEP cage, the majority will be recovered in the final step.

![Figure 11: Intermediate Step in DEP Cage Shift](image)

Another way to reduce the effect of parasitic cages is to minimize the gap between electrodes, seen in Figure 12. This will both minimize the attraction basin of a parasitic cage and only allow for the entrapping of similar sized particles, possible eliminating all particles trapped. This kind of spacing is only possible using MEMS fabrication techniques, instead of the PCB techniques used to make this device.

![Figure 12: Minimized Gap between Electrodes affect on Parasitic Cages](image)
Concentration Increases with Microbeads

A time evolution of device is shown in Figure 4. In a), the device and DEP are turned off with the microbeads scattered at the bottom of the microchamber. Upon activation, DEP cages form above specified electrodes in b). Figures c) through e) show DEP cages being manipulated by being merged into each other, effectively increasing the concentration of particles in a chosen area.

In this experiment, microbeads of 3.46 µm diameter are suspended in distilled waters. Electrodes are driven at 100 kHz 10 Vpp. In the diagram shown in Figure 4, the concentration of the microbeads is continually being driven towards the center, forming one large concentration. One could potentially merge DEP cages at several points depending on the electrode configuration.

Comparison to Voltage Simulation Results

Microbead experiments result in the formation of a cage with a distribution of particles far too complex to be modeled at the level of individual particles, as this would require the integration of a time factor and dilution equations in conjunction with DEP forces. However, in our case, the microbead diameter (3.46 µm) is much less than the diameter of the DEP cage (100µm). This allows the following assumptions:

- Particle cloud within the DEP cage can be modeled as homogenous
- Permittivity and Conductivity depend solely on the ratio between the volume of microbeads and suspending medium in the cylinder (distilled water).

With these assumptions, it is possible to simulate the electric field using FEMLAB in a 2-D perspective, corresponding to a cross section of the device with circular cross section cages. An electric field simulation is performed to calculate the resistance without particles, followed by four simulations to calculate the $R_{m \text{wp}}$, for each of the concentration steps. The initial radius of the cylinder is determined by fitting the sensing output to the $R_{m \text{wp}}$ value. Thus, if $Vol_0$ and $r_0$ are the initial cylinder volume and radius, merging $n$ cages the volume becomes $Vol_n = n*r_0$ and $r_n = n^{1/2} * r_0$. Figure 13 shows the correlation between measured and simulated results, displaying a strong correlation with a starting radius of 25 µm, fitting with optically determined measurements.
Figure 13: Comparison between simulated and measured output amplitude for the central electrode for 3.46μm polystyrene microbeads in distilled water (σ = 0.5μs/cm, stimulus: 10V at 100 kHz). For the simulations a unit volume of V= πr₀^2 has been used, where r₀= 25μm, L= 1cm [1]

The experiments were verified by repetition using *S. cerevisia*, a bakers yeast that has been grown at 25°C in a Sabaroud medium (Oxoid). The yeasts have been grown for 48 hours, harvested by centrifugation, washed twice with 25mL of physiological solution (0.9% NaCl) and once in 25mL of a 280-mM mannitol solution. The dielectrophoretic behavior of *S. cerevisiae* cells suspended in 280-mM mannitol at a changing frequency has been analyzed in the proposed device by microscopic observation. Mannitol solution is used instead of the normal physiological solution to reduce conductivity within the device, while preserving osmotic pressure. An increase in conductivity would lead to heating of the buffer solution, in addition to the shielding of the electric field by ions in the solution. Tests of *S. cerevisia* in the intended frequency range (30 kHz–1 MHz), displays a pDEP behavior in frequencies above 200 kHz. Thus, a 100 kHz frequency will be used to allow nDEP behavior to trap the yeasts in the DEP cages. Frequencies lower than 30 kHz has been avoided to prevent electrolysis. The same procedure is used for *S. cerevisiae* as with the microbeads: The device is filled with a suspension of *S. cerevisiae* in 280-mM mannitol. The electrodes are energized with 100 kHz frequency with 10V amplitude. The concentration cycle is repeated 5 times, increasing the concentration in the central cage by a factor of 9. Sensing values measured after each concentration cycle is displayed in Figure 14.
Figure 14: Measured output amplitude for the central electrode as a function of the number of merged cages for *S. cerevisiae* in 280-mM mannitol solution. (σ=0.5μs/cm, stimulus: 10V at 100 kHz) [1]

**Recommendations**

*Removal of Parasitic Cages*

In order to remove unwanted parasitic cages from the bottom of a microchamber, we propose to embed electrodes into the substrate via ion implantation.

*Manufacturing of a Micro Scale Device*

The device as so far described has been at a rather large scale, with the device reservoir thickness at 250μm, and the electrode spacing at size at 200μm. While this is sufficient for a device with only a few electrodes, any device requiring more than 3 electrodes will range above 1mm in size. We thus propose a scaling of the device by an order of magnitude, whereby electrode size and spacing is only 20μm, and reservoir thickness is reduced to only 50μm. Size is limited by both the properties of DEP, and the particle size to be used. There exist many papers [2,3] indicating that DEP can still be used at this scale, so scale has been chosen to allow for the manipulation of cells, which at most can be 10μm in diameter. With 20μm spacing, cages can at most be 40μm in diameter, allowing for a reasonable amount of the largest cells to be trapped. With the reduction
in size, it is thus possible to have an array of 100 electrodes on a device measuring only slightly larger than 4mm.

Our proposed device will be constructed with three separate wafers; a base layer containing electrodes, central layer to make up the fluid reservoir, and a top transparent conductive layer to allow observation as well as include fluid channels to fill each device. Listed below is a sequence outlining device construction. Cross sectional view is on the left, top view on the right.

**Key:**

- Blue: Silicon - Wafer 1
- Green: Photoresist
- Teal: Silicon - Wafer 2
- Orange: Silicon Oxide
- Black: Mask
- Blue: Ion Implantation - Boron

**Base Wafer:**

Step 1: Base layer consisting of silicon wafer base, with layer of silicon oxide and photoresist.

Step 2: Mask pattern inverted from intended electrode pattern.

Step 3: Removal of Photoresist

Step 4: Dry Plasma etching removal of silicon oxide.
Step 5: Removal of Photoresist using acetone

Step 6: Ion implantation of electrode channels

Step 7: Removal of silicon oxide via plasma etching with CF$_4$

Reservoir Wafer:
Step 1: Lap polish of wafer to reduce thickness to 50μm.

Step 2: Growth of SiO$_2$ oxide layer, and removal from bottom.

Step 3: Spin deposition of photoresist layer and proper mask.
Step 4: Exposure to light and removal of photoresist.

Step 5: Dry plasma etching of silicon oxide.

Step 6: Removal of photoresist using acetone.

Step 7: KOH etching of silicon wafer.

Step 8: Removal of silicon oxide via plasma etching with CF₄

Alignment and Assembly
Step 1: Wafer alignment and bonding of base to reservoir layer, allowing access to electrodes.
Create an array of devices with a common reservoir

With the reduction in size of the device, we are proposing the creation of an array of DEP cage devices, linked together by a single central reservoir. Since manual filling of a new device would be extremely difficult given its size, linking an array of devices to a larger reservoir would allow filling of multiple devices at once. The advantages of an array of devices also allows for larger scale operations. With individual control of each device, a sample containing many different particles and respective concentrations can be routed to a large number of devices. At each of these locations, the proper frequencies and amplitudes can be selected to provide selective concentration increases of a particular particle of interest. Thus, rapid experiments can be conducted to either separate known particles, or identify particle makeup based on input values corresponding to certain particles. The device array we propose would be constructed in a manner similar to Figure 15.

The top sealing layer can incorporate this microchannel pattern, allowing each channel to empty into the device reservoir. The central reservoir can be a simple hole in the sealing layer, and the microchannels can be fabricated using conventional micromilling. The layer can thus be placed...
with microchannels on the bottom to seal the devices and microchannels against the silicon wafer.

**Conclusions**

The utilization of engineering tools and techniques towards addressing primary biomedical problems, i.e. concentrating particles within a sample for biodetection, providing a novel view into the integrative nature of this course. Concepts involving Lab-on-a-Chip design principles, DEP actuation and impedance sensing provide an encompassing review for microfabrication techniques. In particular, we delved into an in depth review in device construction and DEP principles and results. Accomplishing our primary goal, we provided a step-by-step protocol and an explanation of design choices chosen by the author in fabricating this device. In addition, the physical principles that drove the device were examined in detail. Lastly, we were able to begin a discussion on where this technology is heading and possible improvements that can be made in the future.
References

Biographies

**Robert Lam** received his Bachelor of Science degree from the University of California, Los Angeles (UCLA) in 2007 and is currently pursuing a Ph.D. degree in Mechanical Engineering at Northwestern University. He is a graduate student researcher in the Nanoscale Biotic-Abiotic System Engineering (N-BASE) Laboratory and is interested in the study of micro and nanoscale biological sciences.

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