Light actuation of liquid by optoelectrowetting

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Abstract

Optical actuation of liquid droplets has been experimentally demonstrated for the first time using a novel optoelectrowetting (OEW) principle. The optoelectrowetting surface is realized by integrating a photoconductive material underneath a two-dimensional array of electrowetting electrodes. Contact angle change as large as $30°$ has been achieved when illuminated by a light beam with an intensity of $65 \, mW/cm^2$. A micro-liter droplet of deionized water has been successfully transported by a 4 mW laser beam across a 1 cm × 1 cm OEW surface. The droplet speed is measured to be 7 mm/s. Light actuation enables complex microfluidic functions to be performed on a single chip without encountering the wiring bottleneck of two-dimensional array of electrowetting electrodes.
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1. Introduction

Surface tension is a dominant force for liquid handling and actuation in microscale. Several mechanisms have been proposed to control surface tension, including thermocapillary [1], electrowetting [2,3], and light-induced surface tension change [4]. Among them, the electrowetting mechanism has received increasing interests because of its fast switching response and low power consumption. The surface tension between the solid–liquid interface is modified by external electric field, which reduces the contact angle. Examples of electrowetting-based microfluidic systems include optical switches [5], digital microfluidic circuits [6], and liquid lenses with variable focal length [7].

Transport of liquid in droplet forms offers many advantages. It eliminates the need for pumps and valves, has no moving parts, and is free of leak and unwanted mixing. For Lab-on-a-chip applications, several fluidic functions, such as liquid injection, transportation, mixing, and separation, need to be integrated on a single chip. This has been achieved recently by Cho et al. [6]. For a general purpose fluidic chip that is capable of manipulating multiple droplets simultaneously requires a two-dimensional array of electrodes to control the local surface tension. However, this results

in a large number of electrodes that presents a challenge for both control and packaging of such chips. The problem becomes even more severe as the droplet size scales down. Though the number of electrodes can in principle be reduced by integrating electronic decoders on the chip, similar to the memory access circuits, this will significantly increase the cost of the chip.

In this paper, we report on a novel mechanism for light actuation of liquid droplets. This is realized by integrating a photoconductive material underneath the electrowetting electrodes. We called this mechanism "optoelectrowetting (OEW)". We have successfully fabricated a prototype chip with 1 cm × 1 cm area. A micro-liter droplet has been successfully transported to any location on the chip. This approach completely eliminates the wiring bottleneck of conventional electrowetting schemes. This concept is extendable to nano-liter or smaller droplets by scaling down the gap spacing and the electrode size.

2. Principal of optoelectrowetting

2.1. General concept

Fig. 1(a) shows the general electrowetting mechanism. A droplet of polarizable liquid is placed on a substrate with an insulating layer between the liquid and the electrode. When

Fig. 1. (a) Conventional electrowetting under dc bias; and (b) optoelectrowetting with an integrated photoconductor under ac bias.

an external voltage is applied, the surface tension at the solid–liquid interface is modified and the contact angle changes. The voltage dependence of the contact angle, $\theta(V_A)$, is described by Eq. (1)

$$\cos[\theta(V_A)] = \cos[\theta(0)] + \frac{1}{2}\frac{\varepsilon}{d\gamma_{LV}}V_A{}^2 \qquad (1)$$

where V_A, d, ε, and γ_{LV} are applied voltage, thickness of insulating layer, dielectric constant of the insulating layer, and the interfacial tension between liquid and vapor, respectively. If an ac voltage is applied, V_A is replaced by the root-mean-square (RMS) voltage [8].

Fig. 1(b) shows the concept of the proposed optoelectrowetting mechanism. A photoconductive material is integrated under the electrodes of conventional electrowetting circuit. The electrical impedance of the liquid, insulator, and photoconductor are serially connected. From Eq. (1), the contact angle change of the droplet on this OEW surface is determined by the voltage drop across the insulating layer.

The frequency of the ac voltage is adjusted such that the impedance of the photoconductor dominates in the absence of light (dark state). Through the voltage divider, most of the voltage drops across the photoconductor and there is very little voltage across the insulating layer. Therefore, the contact angle remains the same as the equilibrium value. Upon illumination of light, the conductivity of the photoconductor increases by several orders of magnitude due to electron–hole pair generation. The impedance of the photoconductive layer becomes much smaller than that of the insulation layer. As a result, most of the voltage drop is now across the insulating layer. The contact angle is therefore reduced by light illumination.

Fig. 2 shows the schematic of the OEW device proposed in this paper. The liquid droplet is sandwiched between a top hydrophobic surface and a bottom OEW surface. The topside is a transparent conductive indium-tin-oxide (ITO) glass coated with 20 nm of Teflon. The OEW structure is realized by integrating a two-dimensional array of electrowetting electrodes on a photoconductive material. In our current design, 20,000 electrodes with areas of 50 µm × 100 µm are employed over a chip area of 1 cm × 1 cm. The photoconductive material employed here is amorphous silicon. It is deposited by plasma-enhanced chemical vapor deposition (PECVD). The electrodes are then covered by a 0.9 µm-thick SiO$_2$ and a 20 nm-thick Teflon. The Al electrode below the photoconductor has a grid pattern to reduce parasitic capacitance.

The principle of moving a liquid droplet on an OEW surface along a light path is shown in Fig. 3. An ac voltage is applied between the top ITO electrode and the bottom Al grid. The voltage drop across the insulator and the electrode is controlled by light. Shining an optical beam on one edge of the liquid droplet decreases the contact angle and creates a pressure difference between two ends of the droplet, as shown in Fig. 3. This forces the droplet to follow the movement of the optical beam. The light actuation scheme described here requires ac bias. Liquid droplet does not move under dc voltage bias because all the voltage drops

Fig. 2. Schematic structure of the optoelectrowetting (OEW) device. A photoconductive material (amorphous Si) is integrated with a matrix electrode array drive liquid by light.

Fig. 3. Principle illustrating light actuation of liquid droplets.

R_w, C_w: resistance and capacitance of water
C_{oxide}: capacitance of between liquid and electron
R_{asi}, C_{asi}: resistance and capacitance of amorphous Si

(a)

Fig. 4. (a) Equivalent circuit of the optoelectrowetting device. Under light illumination, the voltage drop across the photoconductor decreases, resulting in an increase of voltage drop across SiO_2. (b) Simulated voltage drop across SiO_2 vs. frequency of the bias voltage for various photoconductivities. The constant c is the normalized photoconductivity.

across the insulating layer even without light illumination. The contact angle on both ends of the droplet decreases and no pressure difference is created.

2.2. Equivalent circuit simulation

The equivalent circuit of the OEW device is shown in Fig. 4(a). The electrowetting electrodes are electrically isolated from each other. The ac voltage drop between the top and bottom electrodes is divided among the water droplet, the SiO_2, and the photoconductor. The voltage drop across the thin Teflon layer coated on the topside ITO glass is neglected because it is very small compared to other parts. The voltage drop across the SiO_2 layer controls the contact angle of the droplet on top of that electrode. It is a function of the ac frequency and the photoconductivity. The photoresponse of the OEW equivalent circuit is simulated using SPICE. Fig. 4(b) shows the simulated voltage drop across SiO_2 versus the frequency of the ac bias for various photoconductivity values. In this simulation, the ac bias voltage is 100 V. The conductivity of water is set to be $\sim 10^{-6}$ S/cm. The dark conductivity of amorphous silicon is measured to be 1.67×10^{-8} S/cm. The dielectric constants of water, SiO_2, and amorphous silicon are 72, 4, 10, respectively. The thickness of the water layer is 500 μm. The values of other geometric parameters are the same as described before. The constant c represents the ratio of the photoconductivity and the dark conductivity

$$c = \frac{\sigma_{photo}}{\sigma_{dark}}$$

where σ_{photo} and σ_{dark}, are photoconductivity under light illumination and the dark conductivity, respectively. Without light illumination, $c = 1$. As shown in Fig. 4(b), when the ac frequency is below 100 Hz, there is a significant voltage drop across the SiO_2 layer even in the dark state. Therefore, the liquid droplet does not move effectively for ac frequencies below 100 Hz. For frequencies above 100 Hz, only a small amount of voltage drops across the SiO_2 layer in the dark state. Under light illumination, the voltage drop across

SiO_2 increases because the photoconductor becomes more conductive. The voltage drop on SiO_2 increases with light intensity until the impedance of the photoconductor becomes negligible. As shown in Fig. 4(b), the increase saturates when $c > 400$. For frequencies above 700 Hz, the impedance of the water becomes comparable to that of the SiO_2 layer. The voltage drop across SiO_2 is reduced. From the discussion above, the most effective frequencies for OEW is between 100 and 700 Hz. This frequency range varies with device geometry. For example, the high frequency limit increases for thinner layer of water because of lower water impedance.

3. Contact angle measurement under light illumination

3.1. Photoconductivity measurement

To effectively change the contact angle by light, the photoconductor needs to satisfy the following criteria:

(1) *Low dark conductivity*: This ensures the voltage will mainly drop across the photoconductor in the absence of light.

(2) *Short carrier recombination lifetime*: This enables fast switching of contact angles and high speed actuation of liquids.

(3) *Visible light response*: Low cost visible light sources (either diode lasers or light-emitting diodes) are readily available.

Amorphous silicon satisfies all three criteria. Its dark conductivity is 10^{-8} S/cm, the carrier recombination lifetime is around one microsecond, and it is responsive to visible light. The photoconductivity of amorphous silicon is characterized using a test device shown in Fig. 5(a). Two coplanar Al electrodes form ohmic contacts with a patterned amorphous silicon. Good ohmic contact is important for precise measurement of the photoconductivity. A white light source with uniform intensity is used for the measurement. The measured photoconductivity versus light intensity is shown in Fig. 6. The conductivity increases by 80 times under illumination of light with an intensity of 65 mW/cm^2.

3.2. Contact angle measurement

To measure the contact angle change, an OEW surface is fabricated on a glass substrate. The thickness of the

Fig. 6. Photoconductivity vs. light intensity for amorphous silicon.

amorphous silicon layer is the same as the sample used in the photoconductivity measurement. The experimental setup is shown in Fig. 5(b). The liquid used here is de-ionized (DI) water. A CCD camera is used to record the side-view profile of the droplet. A 500 Hz, 100 V ac signal is applied. Fig. 7 shows the side-view profiles of the droplet in the dark and under light illumination of 65 mW/cm^2 intensity, respectively. The contact angle is measured from the captured image of the droplet.

Since the electrowetting electrodes only covers part of the OEW surface, we need to consider the fill factor of the electrodes when we calculate the change of contact angles due to OEW effect. Since the size of the droplet is much bigger than that of an electrode, the OEW surface can be treated as a composite surface. The contact angle observed in the experiment is an average effect. The average contact angle is described by the equation

$$\cos[\theta] = f_1 \cos[\theta_1(V, I)] + f_2[\theta_2(V)] + f_3 \cos[\theta_3] \qquad (2)$$

where f_1, f_2, f_3 are the fill factors of the electrowetting electrodes, the interconnect lines for bias, and the areas without any metals, respectively; θ_1 the contact angle on the electrode and is a function of bias voltage and light intensity; θ_2 the contact angle on the wire and is a function of bias voltage only because the wire is directly beneath the SiO$_2$;

(a)

(b)

Fig. 5. Experimental setup for: (a) photoconductivity measurement; and (b) contact angle measurement on optoelectrowetting (OEW) surface.

Without Light   **Light Intensigy: 65mw/cm^2**

Fig. 7. Side-view profiles of the droplets with and without light illumination.

Fig. 8. Contact angle of a water droplet vs. light intensity on an OEW surface.

Fig. 9. Photograph and microscope picture of the OEW device.

and θ_3 is the contact angle on Teflon and is a constant. For the device described in this paper, the contact angle change due to bias wires is less than $3°$.

The measured contact angle versus light intensity is shown in Fig. 8. The simulated result is also plotted in the same figure. In our theoretical calculation, the conductivity of water is assumed to be 10^{-6} S/cm. The parameters, V_A, d, ε, and γ_{LV}, used in Eq. (1) are 70 V, 1 μm, $4 \times 8.854 \times 10^{-12}$ F/m, 73 mN/m, respectively. For simplicity, we use linear approximation for the relationship between photoconductivity and light intensity (Fig. 6). In this device, the measured contact angle saturates at around $75°$. This saturation results from the limitation of electrowetting. The mechanism of contact angle saturation is not fully understood. Several groups have

proposed different mechanisms to explain this phenomenon [8–11].

4. Experimental demonstration of liquid transport by light

Fig. 9 shows the photograph and microscope picture of the OEW device. The chip area is 1 cm × 1 cm, and the area of each Al electrode is 50 μm × 100 μm. Over 20,000 electrodes have been fabricated on the OEW surface. To demonstrate light actuation, a water droplet with a diameter of 2 mm is sandwiched between a Teflon-coated ITO glass and an OEW surface with a gap spacing of 0.5 mm. A 4 mW laser at 532 nm wavelength is used to drag the liquid droplet. The droplet is successfully moved across the 1 cm × 1 cm surface by the laser beam. A droplet speed of 7 mm/s was observed. The speed is currently limited by the scanning speed of the laser. Fig. 10 shows four snap shots of the video recording showing the transport of the liquid droplets. The

Fig. 10. Images of liquid transport across a 1 cm × 1 cm OEW area actuated by an optical beam.

laser illuminated spot at the leading edge of the droplet is also visible.

5. Conclusion

A novel optoelectrowetting mechanism has been proposed to move liquid droplets by light. This mechanism combines electrowetting with light response of photoconductors. Light actuation enables a large number of electrowetting electrodes to be addressed without wiring bottlenecks. Experimentally, over 20,000 electrodes have been integrated on a 1 cm × 1 cm area and only a single electrical bias is needed for the entire device. Amorphous silicon is chosen to be the photoconductive material because of its low dark conductivity, visible light response, and short carrier recombination lifetime. Contact angle reduction as large as $30°$ has been experimentally observed under 65 mW/cm^2 light illumination. Movement of liquid droplet at 7 mm/s across a 1 cm × 1 cm OEW surface has been successfully demonstrated using a 4 mW laser beam.

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Biographies

Pei Yu Chiou received BS degree in mechanical engineering from National Taiwan University, Taiwan, in 1998. He is currently a doctoral student in UCLA electrical engineering with major in MEMS. His research interest is in optical MEMS and Bio-MEMS. He is doing research about optical actuation of microfluid.

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Chang-Jin Kim received the PhD degree in mechanical engineering from the University of California, Berkeley, in 1991 with a study on MEMS. He received the BS degree from Seoul National University and MS from Iowa State University with the Graduate Research Excellence Award. He joined the faculty at UCLA in Mechanical and Aerospace Engineering Department in 1993 after post-doctoral work at UC Berkeley and the University of Tokyo. His research is in MEMS, especially the issues related to mechanical engineering, including design and fabrication of microstructures, microactuators and systems, and use of surface tension in microscale. He has established a formal MEMS PhD major field in his department and is active in various MEMS professional courses. Professor Kim is the recipient of the 1995 TRW Outstanding Young Teacher Award and the 1997 NSF CAREER Award. Professor Kim served as Chairman of the Micromechanical Systems Panel of the ASME DSC Division in 1996 and co-organized the Symposium on Micromechanical Systems between 1994 and 1996 for the ASME International Mechanical Engineering Congress and Exposition (IMECE). Professor Kim also organized the 1996 ASME Satellite Broadcast Program on MEMS. He served as General Co-Chairman of the 6th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA'97) and served in the Technical Program Committees of the IEEE MEMS Workshop, International Conference on Solid-State Sensors and Actuators (Transducers), and the SPIE Symposium on micromachining and microfabrication. Currently, he is serving in the Executive Committee of ASME MEMS Subdivision as a subject editor for the IEEE/ASME Journal of MEMS.

Ming C. Wu received his BS degree in Electrical Engineering from National Taiwan University in 1983, and the MS and PhD degrees in Electrical Engineering and Computer Sciences from the University of California, Berkeley in 1985 and 1988, respectively. From 1988 to 1992, he was a Member of Technical Staff at AT&T Bell Laboratories, Murray Hill. In 1993, he joined the Faculty of Electrical Engineering, Department of UCLA, where he is currently Professor. He is also Director of UCLA's Nanoelectronics Research Center, and Vice Chair for Industrial Relations. His current research interests include Micro Electro Mechanical Systems

(MEMS), Optical MEMS (or MOEMS), biophotonics, microwave photonics, and high speed optoelectronics. Dr. Wu was the founding Co-Chair for IEEE LEOS Summer Topical Meeting on Optical MEMS in 1996. The meeting has now evolved into IEEE LEOS International Conference on Optical MEMS that are hosted in Europe, Asia, and US. Dr. Wu has also served in program committees of many other conferences, including optical fiber communications (OFC), conference on lasers and electro-optics (CLEO), IEEE Conference on Micro Electro Mechanical Systems (MEMS), LEOS Annual Meetings (LEOS), International Electron Device Meeting (IEDM), Device Research Conference (DRC), International Solid-State Circuit Conference (ISSCC), and Microwave Photonics (MWP) Conferences. Dr. Wu has published over 340 papers, contributed 4 book chapters, and holds 10 US patents. He is a David and Lucile Packard Foundation Fellow (1992–1997), and an IEEE Fellow.