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# EFFECT OF SURFACE ROUGHNESS ON THE FABRICATION OF ELECTROWETTING DISPLAY CELLS AND ITS ELECTRO-OPTIC SWITCHING BEHAVIOR

PALANIVELU SURESHKUMAR, MIYOUNG KIM,
EUN GYOUNG SONG, YOUNG JIN LIM and SEUNG HEE LEE*
*Polymer Fusion Research Center,*
*Department of Polymer Nano-Science and Technology,*
*Chonbuk National University, Chonju,*
*Chonbuk 561-756, Korea*
**lsh1@chonbuk.ac.kr*

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Electrowetting is a new class of reflective display based on electric field controlled movement of oil/water interface across a hydrophobic layer. The focus of this paper is to fabricate electrowetting cells on a rough hydrophobic surface and to study its effect on kinetics of electrowetting. The surface roughening found effective in two ways in the design and operation of the electrowetting device: (i) It enhances the coating of photoresist (PR) on the hydrophobic surface, which is normally difficult due to low surface energy of Teflon and (ii) the roughness changes the contact angle of the liquid (oil), which in turn changes the electro-optic switching behavior of the device. The kinetics of optical switch was checked by calculating theoretically the white area fraction (WA%), which is a measure of optical switching in electrowetting display by changing the roughness of the hydrophobic surface. The present study showed that the optical performance found to increase with the increase of roughness of the hydrophobic surface.

*Keywords*: Electrowetting; display device and electro-optics.

## 1. Introduction

Reflective displays are generally considered as one of the promising technologies for the future mainly for portable applications. Although a number of technologies have been proposed for use in reflective displays,[1–4] many of them lack the fast response speed required for showing video content. Electrowetting display demonstrated by Hayes and Feenstra[5] is considered as an important candidate among the reflective display technologies since it can be used to make displays that are extremely bright and energy efficient — two critical features for portable devices, such as mobile phones, MP3 players, and cameras.

The field of electrowetting is currently the focus of increasing experimental and theoretical activity — not only for display applications but also for other applications like adaptive lens systems,[6] and lab on a chip.[7] The principle of electrowetting is based on the electric field controlled two-dimensional movement of an oil and water across a hydrophobic fluoropolymer insulator, which will create color displays four

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[*] Corresponding author.

times brighter than a reflective liquid crystal display (LCD).[5] Hence it is very important to understand the two-dimensional oil motions in the electrowetting device.

Although many studies have been devoted to the electrowetting behavior of such systems for the interface between the immiscible fluids, a complete understanding of the factors influencing the oil film motion based on electrowetting is lacking. The two main objectives of this paper are to study the effect of roughening of the fluoropolymer surface for good adhesion of PR layer required for pixel wall and to study theoretically the influence of surface roughness on the kinetics of the optical switch. For this we explore the electrowetting behavior and the dynamics of pixels as a function of the important parameters, like addressing voltage and roughness factor.

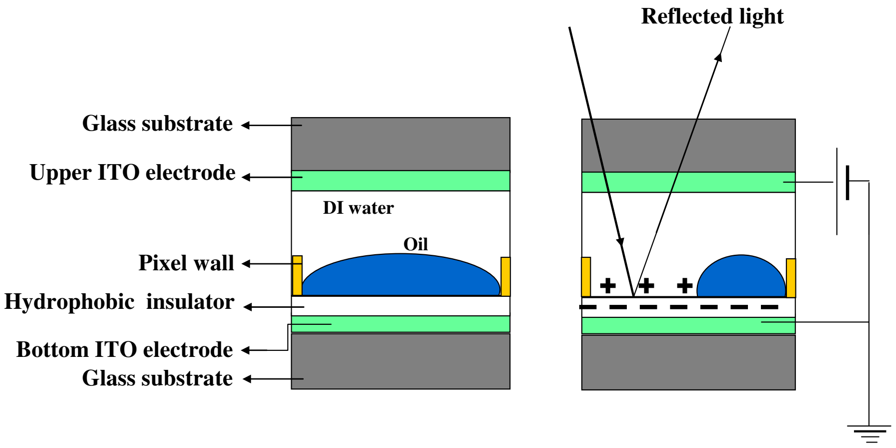
## 2. Principle of Electrowetting Display

The electrowetting display principle utilizes the voltage-controlled movement of a colored oil film adjacent to a white substrate by applying electrical signals to top and bottom indium-tin-oxide (ITO) electrodes. The electrowetting cell shown in Fig. 1 is an optical stack comprising of a white fluoropolymer hydrophobic insulator, colored oil, and water. In the absence of a voltage, the oil forms a continuous film between the hydrophobic insulator and water since $\gamma_{o,w} + \gamma_{o,i} < \gamma_{w,I}$, where $\gamma$ is the interfacial tension and subscripts $o$, $w$, and $i$ denote oil, water, and insulator, respectively.

When a voltage difference is applied across water and an electrode underlying the hydrophobic fluoropolymer insulator, the stacked state is no longer energetically favorable since an electrostatic term is added to the energy balance. The system can lower its energy by moving the water into contact with the insulator (i.e. the fluoropolymer becomes hydrophilic and hence the water wetting the fluoropolymer) thereby displacing the oil to a corner of the pixel (Fig. 1(b)) and thereby exposing the underlying white surface. In this manner, the optical properties of the stack when viewed from above can be tuned between a colored off-state and a white on-state. The tuning of colored off-state and white on-state is possible only if the pixel size is sufficiently small so that the eye averages the optical response. Thus a simple and highly reversible optical switch is driven by electrowetting effect.

## 3. Fabrication of Electrowetting Cell

Electrowetting device shown in Fig. 1 was fabricated on an ITO-coated glass substrate, which is transparent (> 90%) and electrically conducting. DuPont Teflon® AF 1600, an amorphous fluoropolymer was first spin coated onto the ITO/glass substrate. After ~22 min baking and annealing cycle, the fluoropolymer forms a transparent 5–6 $\mu$m thick dielectric film. Next, a hydrophilic grid is to be optically patterned



(a) (b)

Fig. 1. Schematic diagram of the electrowetting cell: (a) colored-off state and (b) white on-state.

from a photo curable polymer, which is a PR material. However, the low surface energy of teflon reduces the bonding ability and hence coating of the commercial PR material. However, surface roughening alters the properties of the fluoropolymer surface allowing it to be bonded with PR. Surface roughening can be achieved either by oxygen plasma treatment or by chemical etching. Owing to its easy availability and economically viable, we have adopted chemical etching using very dilute sodium etchant for roughening of the teflon layer. During this process the sodium etchant solution strips some of the fluorine atoms from the carbon chain of the outer layer of the teflon, which is made of long chain carbon molecules bonded to fluorine atoms. In the present work, a positive PR (AZ electronic material, Korea) was spin coated after sodium etching and then pixels were patterned on fluoropolymer by photolithography.

A few hundred of $\mu$L of deionized (DI) water and a few hundred nL of mixture of colored oil (silicone oil) and oil blue N (0.1 wt%) both procured from Sigma Aldrich-Korea, are dosed over the array of electrowetting cells one after the other. The colored oil mixture ($\gamma < 25$ dynes/cm) forms a continuous film between the water ($\gamma < 73$ dynes/cm) and the hydrophobic dielectric ($\gamma < 20$ dynes/cm). This water/oil/hydrophobic-dielectric layered geometry is due to interfacial surface tension relationship $\gamma_{o,w} + \gamma_{o,i} < \gamma_{w,I}$ discussed above.

## 4. Working

The fabricated electrowetting device is operated as follows. Under conditions of zero applied bias to the water layer, interfacial surface tensions cause the black oil to form a continuous film between the water and hydrophobic-dielectric layer (Figs. 1(a) and 2(a)). The application of voltage and resultant increased wetting of the water layer causes the oil layer to be displaced to a fraction of pixel cell area, and exposing the underlying white surface as shown in Fig. 1(b). The photograph in Fig. 2(b) shows a typical oil retraction observed where in the oil moves into one of the corners of the 150 $\mu$m$^2$ pixel. It is also observed that the oil contraction is not uniform in all pixels, which is a common problem in electrowetting displays and this can be overcome by using patterned ITO electrode.[8–10] The balance between electrostatic and capillary forces determines how far the oil is moved to the side of the cell. In this manner, the optical properties of the stack when viewed from above can be tuned between a colored off-state and a white on-state.

## 5. Effect of Surface Roughness on Electro-Optic Characteristics of the Cell

When voltage is applied, the increased wetting of water layer on insulator causes the oil layer to be displaced to a fraction of the pixel and in this process it is assumed that the oil film on the hydrophobic surface contracts maintaining its spherical cap with circular base area. This field-dependent wetting process, that is, electrowetting behavior is governed by a combination of the Lippman and Young equations for electrowetting in a three-phase water/oil/dielectric system[11–13]:

$$\cos\theta = \cos\alpha - \frac{\varepsilon_0 \varepsilon_r V^2}{2d\gamma_{ow}}, \tag{1}$$

where $\theta$ and $\alpha$ are the contact angles of the liquid with and without applied field. $d$, $\varepsilon_r$, and $\gamma_{ow}$ are insulator thickness, dielectric constant, and oil/water interfacial tension, respectively. Since when there is no applied voltage, the oil film spreads completely

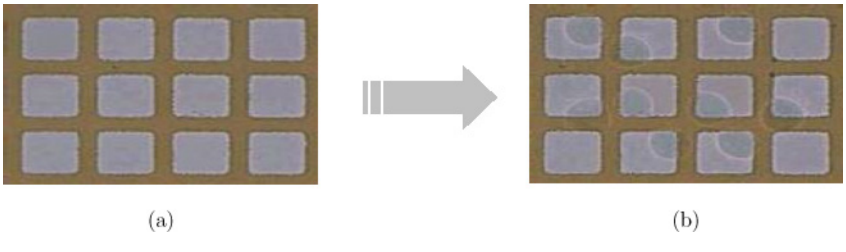

(a) (b)

Fig. 2. Top view images of the oil contraction in pixels when viewed through microscope off-state (without field) and (b) on-state showing oil contraction to a corner (with applied field).

over the teflon layer the value of $\cos\alpha$ can be taken as 1. Then "Eq. (1)" becomes

$$\cos\theta = 1 - \frac{\varepsilon_0\varepsilon_r V^2}{2d\gamma_{ow}}. \tag{2}$$

Area of the circular oil base $A_{\mathrm{oil}}(V)$ on a pixel for a given voltage $V$ in terms of contact angle of oil can be written as[11]

$$A_{\mathrm{oil}}(V) = \pi\sin^2\theta(V) \times \left(\frac{V_{\mathrm{oil}}}{\left(1 - \frac{3}{2}\cos\theta(V) + \frac{1}{2}\cos^3\theta(V)\right)}\right)^{2/3}. \tag{3}$$

Similarly, oil base area $A_o$ before the application field is written as

$$Ao = \pi\sin^2\alpha \times \left(\frac{V_{\mathrm{oil}}}{\left(1 - \frac{3}{2}\cos\alpha + \frac{1}{2}\cos^3\alpha\right)}\right)^{2/3}, \tag{4}$$

where $V_{\mathrm{oil}}$ is the oil volume dosed to the pixel.

The top view images of the pixel, when viewed by means of video camera of the optical microscope, are shown in Fig. 2(b). During oil contraction, the pixel area without oil gives the white area (WA%), which is the measure of electro-optic behavior of the cell, defined as[11]

$$\mathrm{WA\%}(V) = \left(1 - \frac{A_{\mathrm{oil}}(V)}{A_{\mathrm{pix}}}\right) \times 100, \tag{5}$$

where $A_{\mathrm{oil}}(V)$ and $A_{\mathrm{pix}}$ denote the pixel area occupied by the oil and the overall area of the pixel, respectively, and $V$ represents the pixel voltage.

Then by substituting "Eqs. (3) and (4)" into "Eq. (5)," the white area percentage of the cell can be calculated theoretically using the following equation:

$$\mathrm{WA\%}(V) = \left(1 - \left(\frac{\sin^2\theta(V)}{\sin^2\alpha}\right) \times \left(\frac{1 - \frac{3}{2}\cos\alpha + \frac{1}{2}\cos^3\alpha}{1 - \frac{3}{2}\cos\theta(V) + \frac{1}{2}\cos^3\theta(V)}\right)^{2/3}\right), \tag{6}$$

where $\theta$ and $\alpha$ are the contact angles of the liquid with and without applied field.

From the above, it is clear that the whole electro-optic behavior of the electrowetting device is due to changes in the wetting and de-wetting behavior of water and liquid on the substrate, by the application of electric field and hence the name electrowetting. Thus wetting is one of the main factors in determining the electro-optic behavior of the electrowetting devices. In this scenario and since we have roughened the surface for effective PR coating for litho graphics fabrication of pixels, we felt that it is worth studying the influence of surface roughness of hydrophobic surface on electrowetting kinetics. So far to the best of our knowledge there is no report on the study of effect of surface roughness on the electro-optic studies of electrowetting display cell. The literature survey reveals that in the recent years there have been remarkable advances in the understanding of wetting of rough surfaces.[14–16] This understanding opens up the possibilities of employing roughness as a new candidate to control the oil movement in electrowetting display cell and hence to study its electro-optic characteristics.

In the present work, we have assumed that by uniform chemical etching, a rough surface with protrusions like pillars of regular geometry is formed on the smooth surface. The basic effect of surface roughening on wetting can be accounted by Wenzel mode and Cassie–Baxter model.[14,17] In the Wenzel model, it is assumed that the space between the protrusions on the surface is filled by liquid whereas in Cassie–Baxter model the space is filled by trapped air.

If we assume the rough surface is formed by an regular array of pillars and the colored oil fills the gap between the protrusions, then according to Wenzel modified Young's equation the apparent contact angle $\theta_a$ of the liquid drop on the rough surface is given by

$$\cos\theta_a = r\cos\theta, \tag{7}$$

where $r$ is the roughness factor ($r = a/A = da/dA \geq 1$) and $\theta$ is the Young equilibrium contact angle. $a$ is the actual area of the surface and $A$ is the apparent area or geometrical area of the surface. If air fills the gap between the protrusions instead of oil, then by Cassie–Baxter model the modified Young equation, the apparent contact angle of the oil is given by

$$\cos\theta_a = \phi\cos\theta - (1 - \phi), \tag{8}$$

where $\phi$ is the fraction of liquid in contact with the solid and $1-\phi$ is the fraction of liquid in contact with trapped air. Assuming that a two-dimensional array of square pillars created on the surface causes roughness, we have calculated the white area percentage for three different applied voltages by substituting contact angles of the Wenzel model and Cassie and Baxter model in "Eq. (6)" for a set of permissible roughness parameters $r$ and $(1 - \phi)$ and the results are depicted in Figs. 3 and 4. From the graphs it is clear that with higher roughness, higher brightness (pixel white area %) can be achieved at lower drive voltage. The figures also show that an over all higher brightness can be achieved when the Wenzel roughness factor $r$ is considered for the same applied voltage range.

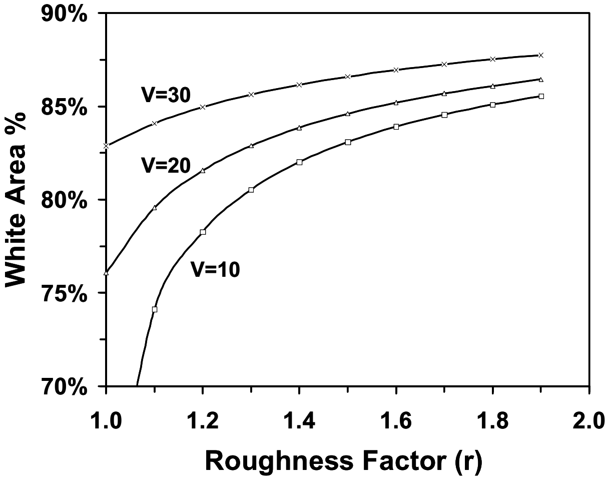


Fig. 3. The electro-optic behavior as a function of Wenzel's roughness factor $r$ for applied voltages 10–30 V.

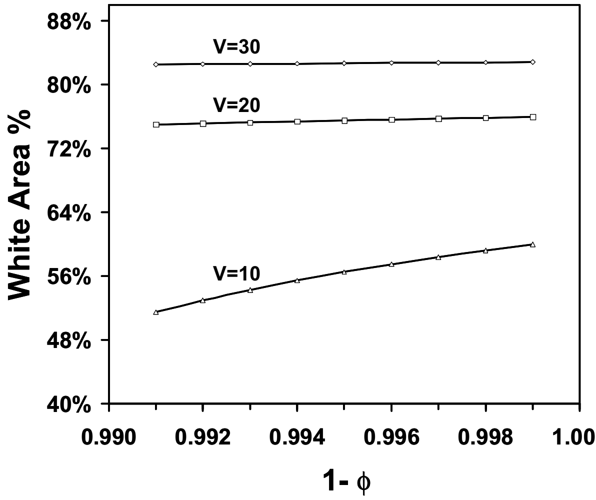


Fig. 4. The electro-optic behavior as a function of Cassie–Baxter roughness factor $(1 - \phi)$ for applied voltages 10–30 V.

## 6. Conclusion

In the present work, we have roughened the hydrophobic surface using sodium etchant and it was found to be effective for an efficient PR coating. The influence of roughness of the hydrophobic surface on the electro-optic behavior of the electrowetting cell was studied theoretically. It showed that in electrowetting display devices roughness of the substrate can be considered as one the important factor in controlling the electro-optic characteristics and a systematic experimental study about the influence of surface roughness on electrowetting is underway.

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