Scalable fabrication of electrowetting displays with self-assembled oil dosing

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Scalable fabrication of electrowetting displays with self-assembled oil dosing is reported. Electrowetting pixel structures consisted of flexible substrate/electrode/hydrophobic dielectric/hydrophilic grid. 20 electrowetting display prototypes were constructed with four pixel sizes ranging from 300×900 to 50×150 μm^2 and with five grid thicknesses ranging from 16.2 to 3.3 μm. Self-assembled oil dosing was achieved by dip coating the substrate through an oil film suspended on water. The oil films in pixels were geometrically flat. Operating voltage increased with pixel aspect ratio. Electrical capacitance and optical absorption calculations confirm that oil thickness is within ±5% of the hydrophilic grid height. © *2007 American Institute of Physics*.
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Electrowetting displays (EWDs) have been demonstrated in reflective,[1] transmissive,[2] and emissive[3] formats with optical efficiencies superior to many conventional display technologies. Introduced by Hayes and Feenstra,[1] EWDs utilize electrowetting[4] to modulate the geometry of a colored oil film in order to create an optical shutter. In addition to higher brightness, EWDs are inherently Lambertian and are capable of rapid milliseconds switching rates for video displays. Furthermore, all solid-phase EWD features can be fabricated with parallel fabrication processes on standard manufacturing equipment. However, electrowetting pixels rely on colored oils that must be precisely dosed into each pixel cell. Achieving parallel and scalable oil dosing presents a challenge since it is a nonstandard process and because it is performed inside an aqueous bath to ensure the oil is localized by interfacial surface tensions.[5] Reported in this letter is a simple, parallel, and scalable self-assembly technique for dosing of oil into EWD pixels. The process uses dip coating of EWDs into a two-phase oil/water bath and is governed by interfacial surface tension. Characterization of completed ~80 000 pixel EWDs reveals that this self-assembly technique results in predictable and highly uniform oil dosing for pixel dimensions ranging from a few millimeters to tens of micrometers. This letter also reports a process for creating a photodefinable hydrophilic pixel grid that is compatible with a wide range of electrowetting oils and solvents. Additionally, the results reported herein are applicable to parallel fabrication of liquid field effect transistors,[6] which are electrowetting-based electrical switches with oil-filled cells. In this letter EWD fabrication and oil dosing are presented. Electro-optical results are then reported for 20 EWD prototypes with varied pixel geometries. Lastly, the role of pixel geometry on oil dosing and operating voltage is discussed.

EWD fabrication is performed on flexible ~125 μm polyethylenenaphthalate (PEN) films (Bekaert Specialty Films, LLC). The PEN substrates were provided with an ~50 nm film of In_2O_3:SnO_2 (ITO) that served as a lower electrode. The ITO was then coated with ~1.6 μm of pinhole-free Parylene C dielectric (2 MV/cm, $\varepsilon_r\sim3$). Next, a fluoropolymer solution such as DuPont teflon AF in fluorosolvent is applied by spin coating, baked, and forms an ~200 nm solid film with a surface energy of 16–18 mN/m. As labeled in Fig. 1(c), the parylene/fluoropolymer stack is herein referred to as the hydrophobic dielectric. A hydrophilic grid of Microchem SU-8 negative photoresist (Microchem, Lot 06030170) was then patterned via photolithography. Spin coating speeds ranging from 200 to 6000 rpm resulted in hydrophilic grid thicknesses of 16.2, 10.4, 8.9, 4.7, and 3.3 μm. The epoxy-based SU-8 resist performs well for EWDs because it (1) does not dissolve, swell, or degrade

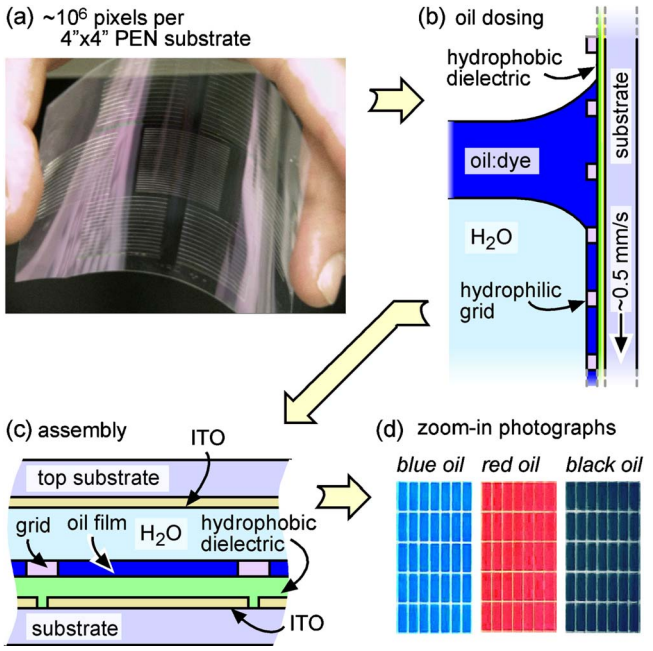


FIG. 1. (Color online) Photographs and diagrams of EWD (a) substrates, (b) self-assembled oil dosing, (c) prototype assembly, and (d) photographs of completed EWDs.

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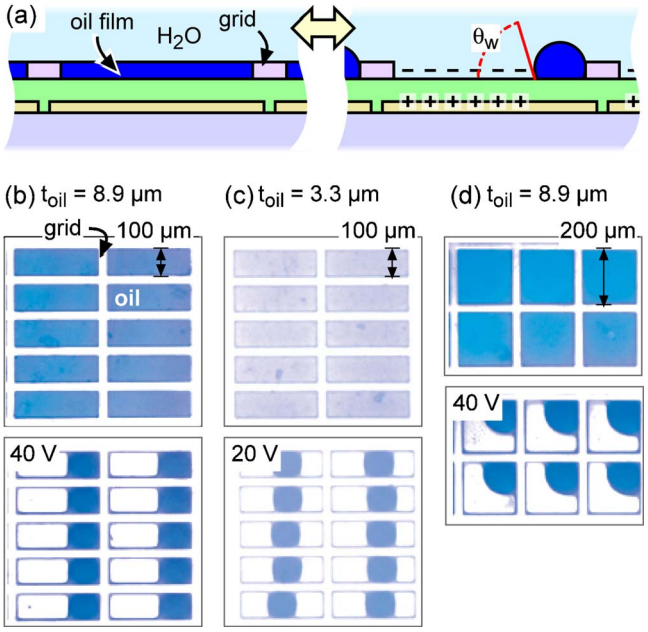


FIG. 2. (Color online) (a) Diagram of electrical switching of an EWD pixel and (b) photographs of blue pixels in operation.

in typical polar and nonpolar electrowetting liquids; (2) during application and development there is no surface fouling of the fluoropolymer; (3) SU-8 can be formulated for a wide range of film thickness; (4) SU-8 is adequately hydrophilic for the self-assembled oil dosing process described herein. The hydrophilic grid patterns that were tested included 300×900, 200×600, 100×300, and 50×150 μm^2. The width of the hydrophilic grid is 25 μm for the largest three pixel sizes and 12.5 μm wide for the smallest. The five grid thicknesses and four pixel sizes provide a total of 20 EWD prototypes for characterization. EWD substrates complete with SU-8 grids are pictured in Fig. 1(a).

In previous work,[2] EWD pixels were covered in water and oil was dosed serially into pixels using a nanoliter syringe. The self-assembled oil dosing process reported in this letter is a parallel process and significantly more scalable. As shown in Fig. 1(b), the EWD substrate of Fig. 1(a) is lowered into a container of colored oil floating upon de-ionized water (~73 mN/m). The floating oil film thickness is greater than several pixel sizes. The oil is dodecane (~25 mN/m, 0.75 g/ml) and is colored with 5–10 wt % of nonpolar blue, yellow, red, or black dye mixtures with spectral characteristics previously reported.[7] As depicted in Fig. 1(b), the nonpolar oil first wets all features of the EWD display. As the substrate is further lowered into the container at ~0.5 mm/s, the water wets the top surface of the hydrophilic grid and cuts the oil. Simultaneously, the oil remains wetted to the grid sidewalls and oil is precisely dosed into each pixel. To further investigate the water wetting, SU-8 films were immersed in a water bath, and advancing and receding oil contact angles were measured to be 80° and 30°, respectively. After oil is dosed into all the cells, the EWD is sealed underwater with a top sealing substrate. A diagram of a completed EWD is shown in Fig. 1(c), and zoom-in photographs of several completed EWDs are shown in Fig. 1(d). Operation of completed EWD pixels is shown in Fig. 2. Electrowetting occurs as increased voltage results in charge accumulation near the three-phase water/oil/dielectric contact line.[4] This charge accumulation alters the balance of interfacial surface tension forces and reduces the water contact angle [θ_w, Fig. 2(a)] from >170° to well below 90°. The reduced water contact angle causes a complimentary contact angle increase in the oil (θ_o), and the oil switches from a film geometry ($\theta_o<10°$) to a spherical cap geometry ($\theta_o>90°$). Several studies[5,8,9] provide a detailed model of the pixel switching mechanism, and therefore switching theory will not be reviewed herein. EWDs have been fabricated on active matrix thin-film-transistor substrates and techniques for 4 bit grayscale have been demonstrated.[10] Although this grayscale operation is satisfactory for electronic paper applications, further improvements are needed for high-image-quality displays.

Photographs of operation for self-assembled EWD pixels are shown in Figs. 2(b)–2(d). Although the smallest pixel sizes reported in this work are 50×150 μm^2, it is expected that the oil dosing scales to even smaller pixel sizes. However, for most display applications smaller pixel sizes are not required. It is visibly obvious that the colored oil thickness is fairly constant across the pixel at zero voltage. This was observed even for the 300×900 μm^2 pixels with 8.9 μm grid thickness. Therefore the oil is likely filled to the top of grid with a sidewall contact angle near 90°. Oil thickness equal to grid height was further confirmed using optical transmission and electrical capacitance measurements. Calculations for both techniques provided oil thickness values that were within ±5% of the grid thickness. As can be seen in the photographs, the change in oil area with voltage is very uniform. Uniform oil coloration and pixel switching was observed down to the smallest pixels which had $3.3\times50\times150$ μm^3 or 25 pl of oil. This confirms that the self-assembled oil dosing technique is capable of at least a few picoliters dosing resolution.

In order to further verify the repeatability of self-assembled oil dosing, all EWD prototypes were characterized by measuring the voltage at which the oil occupies 50% of the pixel area. Figure 3(a) plots this voltage for 50% oil area versus the grid thickness. The same data are plotted in Fig. 3(b) versus pixel size. Both plots show an increase in voltage for 50% oil area as the grid and oil thickness (t) increase or as pixel width (w) decreases. Both plots [Figs. 3(a) and 3(b)] are captured in Fig. 3(c) by plotting the voltage for 50% oil area versus pixel aspect ratio (t/w). As pixel aspect ratio increases, there is a proportional increase in voltage for 50% oil area. This can be explained as follows. The electrowetted contact angle is predicted[4] as $\theta_w \approx \cos^{-1}(CV^2/2\gamma-1)$, where C is the hydrophobic dielectric capacitance (F/m^2) and γ the water/oil interfacial surface tension (N/m). As the pixel aspect ratio (t/w) increases, achieving 50% oil area will require a smaller θ_w and therefore a larger voltage. This is shown qualitatively in the inset diagrams of Fig. 3(c). This trend is comparable to prior investigations[8] except that in this work the initial oil geometry is flat (i.e., not a spherical cap). A starting geometry that is flat increases the required operating voltage. However, for displays a flat oil layer is preferred for maximum optical contrast between on and off pixel states. Elaborating further, it is observable in pixel photographs of previous work that spherical cap geometry at zero voltage results in thinner oil at the pixel edges and undesirable light leakage.[2,8] Therefore, the self-assembled oil dosing approach reported here is further beneficial as it promotes maximum optical performance

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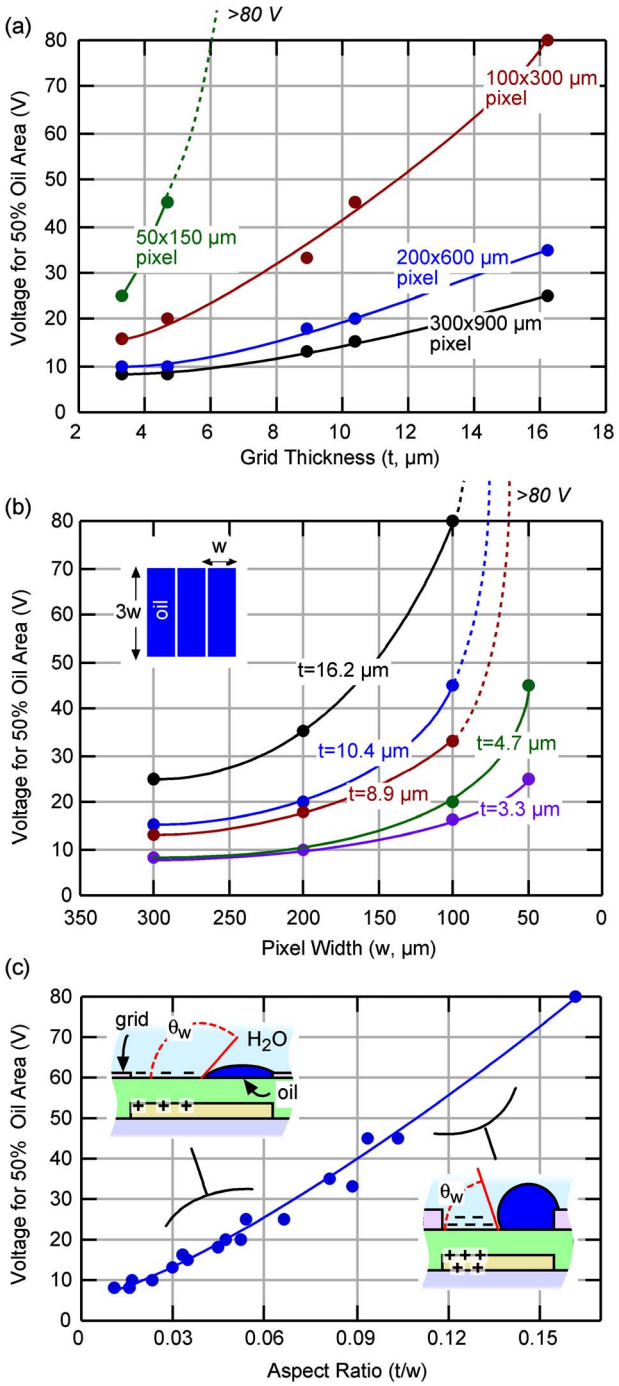


FIG. 3. (Color online) Operating voltage required for 50% oil area vs (a) grid thickness, (b) pixel width, and (c) pixel aspect ratio. The dotted lines indicate the expected voltage requirements beyond the 80 V maximum used in this work.

for EWDs. For very high aspect ratios, the required operation voltage exceeded the maximum of 80 V utilized herein [dotted lines, Figs. 3(a) and 3(b)]. At first glance, one might argue that for small pixel width (w), one should simply reduce the grid and oil thickness (t) to sustain a low aspect ratio and low voltage. However, as observed in the photographs of Fig. 2(c) and predicted by the Beer-Lambert law, thinner oil is not sufficiently opaque for high-contrast EWD operation. One could improve the dye optical strength and/or maximum solubility in dodecane. However, a more readily achievable approach is to increase dielectric capacitance (C) and decrease the oil/water interfacial surface tension (γ) through addition of surfactant. In order to experimentally prove reduced operating voltage, additional EWDs were fabricated with water:sodium dodecyle sulfate ($\gamma < 20$ mN/m) and the voltages required for operating 50×150 μm^2 pixels were reduced from ~40–50 V down to ~10–15 V. The effect of pixel width (w) and grid thickness (t) on switching speed should also be discussed. The switching speed is generally limited by the slower off switching speed (voltage off). This is particularly pronounced for larger pixel widths, where the oil/water contact line must travel the most distance in the pixel. Also, for small aspect ratio cells (large w, small t), switching the pixel on only requires a small change in θ_w. Therefore, when the pixel is switched off, there is a smaller imbalance of interfacial surface tensions at the water/oil/dielectric contact line and less force to drive the oil back to a film geometry. Switching speed was found to be >100 ms for the largest pixel widths and <10 ms for the smallest pixel widths. Lastly, it is important to note that the data of Fig. 3(c) are highly predictable, further confirming the repeatability and precision of the self-assembled oil dosing approach reported in this letter.

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