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Versatile electrowetting arrays for smart window applications-from small to large pixels on fixed and flexible substrates

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ABSTRACT

Versatile electrowetting (EW) arrays were fabricated with small to large pixels, on fixed glass and flexible polymer substrates, for smart window applications. EW prototypes on glass substrates were constructed with pixel sizes ranging from 50 μm × 150 μm to 2 mm × 2 mm. The dosing of the array with colored oil was achieved by dip coating the substrate through an oil film suspended on a water bath. The arrays can be driven by either DC or AC voltage. Optical transmission of the prototypes can be modulated from ~5% to > 70% with a relatively low applied voltage of ~15 V. The switching speed of the prototype depends on oil properties and cell size, typically ~10 ms for 300 μm × 900 μm pixel cells. Flexible color EW array prototypes have been fabricated on polymer polyethylene terephthalate (PET) substrates, which can be switched reversibly by applying a relatively low voltage difference between the water and bottom electrode. The EW specifications are maintained even when the prototype is mechanically flexed. These results indicate the promise of EW technology for smart window applications.

1. Introduction

Increases in energy consumption and issues of global warming and environment pollution are increasing the consideration of energy efficiency in industry, transportation, and residential design, among others. The windows of a house, building and automobile represent one of the least energy-efficient components. A new class of windows called “smart windows” or “dynamic tintable windows” has been attracting rapidly increased attention [1–3], owing to their potential to change optical properties, such as the solar factor and the transmission of radiation in the solar spectrum, in response to electric voltage or current or to change by environmental conditions like solar radiation (photochromic) or temperature (thermochromic). The use of smart windows may drastically reduce the energy consumption of buildings by reducing cooling and heating loads and the demand for electrical lighting. Various technologies are used in smart windows, such as chromic materials [4], liquid crystals [5], and electrophoretic or suspended-particle devices [6]. Smart window products based on these technologies are becoming available in the market. One of the shortcomings of current technologies is long switching time for coloration and bleaching [7]. This issue is likely to become even more serious as the size of devices increases to cover larger windows. Another important consideration for future smart windows is the development of ultra-thin and flexible products to be used in curved glass windows. Finally, the durability of smart windows is also crucial.

The electrowetting (EW) effect [8,9] provides an interesting approach for smart windows, through the modification of the wetting properties of a hydrophobic surface with an applied electric field. The EW effect can provide rapid manipulation of two immiscible liquids (one of which is clear and the other containing dye) on a micrometer scale [10]. EW has a number of interesting applications which have recently been developed, such as optical filters, [11] adaptive lens systems, [12] and lab-on-chip [13] in addition to reflective displays [8,14]. Compared with other technologies, the EW technology has several advantages: switching speeds in millisecond range, wide viewing angle and relatively low power consumption [15].

In this work, versatile EW arrays consisting of a range of small (50 μm × 150 μm) to large (2 mm × 2 mm) pixels fabricated on polymer and glass substrates are reported for smart window applications. The optical transmission of the prototypes in the visible range is demonstrated. Flexible EW smart window prototypes are fabricated and the flexible operation is demonstrated at a relatively low voltage.

2. Materials and methods

The single color EW array device structure illustrated in Fig. 1a consists of a dielectric-covered transparent bottom electrode on the glass substrate, a hydrophobic insulator layer (Cytop CTL-809M),

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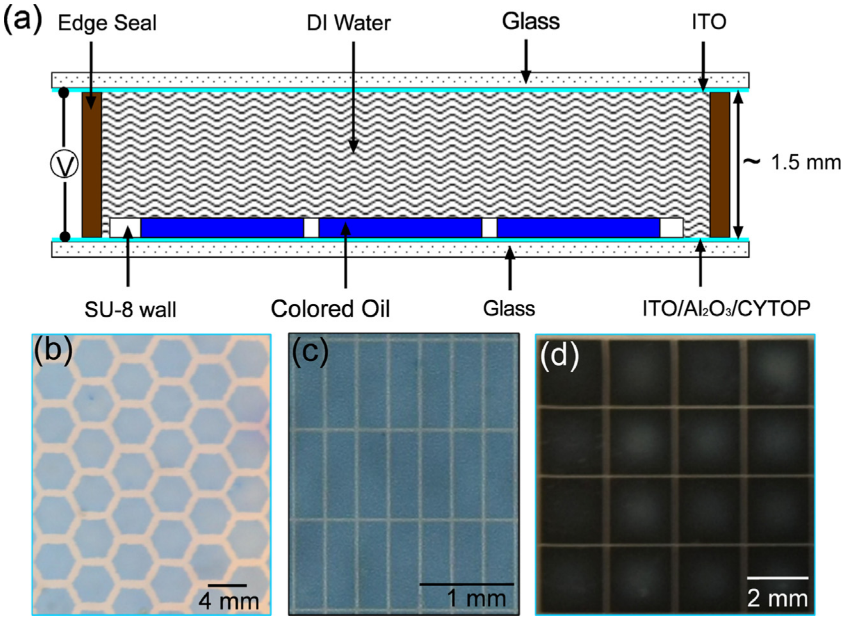

Fig. 1. Single-color EW arrays on glass substrates: (a) schematic diagram of device structure; photographs of several arrays; (b) 2 mm hexagonal (blue) pixel; (c) 300 μm × 900 μm rectangular (blue) pixel; and (d) 2 mm × 2 mm square (black) pixel. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

a hydrophilic grid (SU-8 photoresist), the two fluids (water and oil), and the top electrode (ITO/glass). Details of the device fabrication process have been previously described [16,17]. The active device area is defined by the hydrophilic grid, which confines the oil by strongly attracting the water. When a negative bias is applied to the water droplet, the resulting field across the hydrophobic insulator effectively increases its surface energy and reduces its hydrophobicity, attracting the polar water molecules to the insulator surface. With increasing bias, the water increasingly displaces the oil layer to the side of the pixel. Fig. 1b, c and d shows zoom-in photographs of assembled color EW arrays with different pixel sizes and shapes.

For the flexible prototype, the device structure is illustrated in Fig. 2a. A 175 μm thick polyethylene terephthalate (PET) was used as the substrate. The hydrophobic insulator (Cytop) and the underlying insulator layers (Parylene C) are typically 100 nm and 1 μm thick, respectively. A ~8 μm high hydrophilic grid uses epoxy-based negative photoresist (SU-8 2010) to confine the oil film in each pixel. All of the processes on the PET substrate were carried out below 150 °C to prevent degradation of the PET film. Multi-element (~1000–2000) arrays with pixel sizes of 200 μm × 600 μm and 300 μm × 900 μm were fabricated. The width of the hydrophilic grid is 25 μm for both arrays. Fig. 2b shows magnified photographs of each layer of the three color arrays (300 μm × 900 μm pixel size) before final assembly of the overall EW device.

3. Results and discussion

3.1. Large pixel array characteristic on fixed glass substrates

The pixel switching process in a typical EW array is illustrated in Fig. 3, which shows a 10 × 10 array with pixel dimensions of 1.5 mm × 1.5 mm from closed to open states under applied AC voltage of 14 V RMS. The process is reversible and can be repeated for many cycles. Moreover, early prototype modules are still fully operable for over 2 years so far. For these square geometry pixels, the black oil is displaced to the four corners of each pixel when the voltage is applied. For rectangular pixels, the oil is displaced to the long sides of the rectangle when voltage is applied.

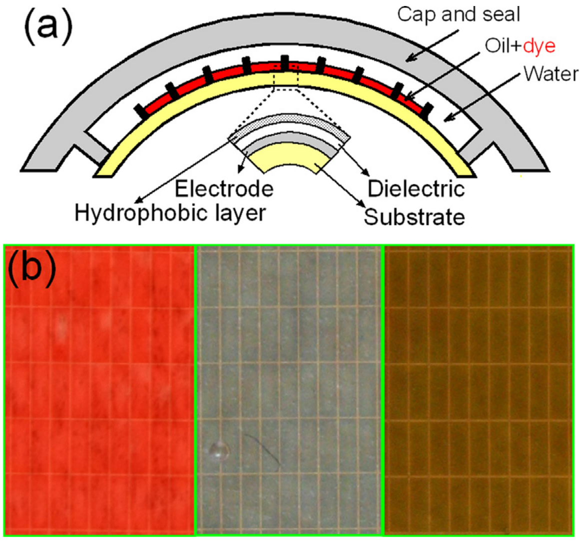

Fig. 2. Color EW array using flexible PET substrate: (a) schematic diagram of device structure and (b) high magnification view of 9 × 5 section of arrays with 300 μm × 900 μm pixels.

This control depends on the array configuration and the properties of grid materials used in the array, which control the oil profile in the pixel (concave vs. convex). If the oil is pinned at the edge of the grid with a convex profile, the oil will be displaced to the center of the pixel when voltage is applied [18]. If the oil is pinned to the edge of the grid with a concave profile, the oil will be displaced to the corners of the pixel. The electromechanical force will break the oil first at its thinnest location, namely in the center (corner) of the pixel in the concave (convex) oil profile.

The full spectrum electro-optic characteristics of a fixed array prototype with black oil were obtained by measuring the transmission over the visible range with and without applied voltage. As shown in Fig. 4a, under zero bias the low surface tension black oil preferentially covers the low surface energy hydrophobic