Displays 37 (2015) 79–85

Contents lists available at ScienceDirect

Displays

journal homepage: www.elsevier.com/locate/displa

Screen-printing fabrication of electrowetting displays based on poly(imide siloxane) and polyimide

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ARTICLE INFO

Article history:
Received 6 September 2014
Received in revised form 17 September 2014
Accepted 22 September 2014
Available online 13 October 2014

Keywords:
Electrowetting display
Printable fabrication
Screen-printing
Polyimide

ABSTRACT

We report a screen-printing fabrication process for large area electrowetting display (EWD) devices using polyimide-based materials. The poly(imide siloxane) was selected as hydrophobic insulator layer, and relatively hydrophilic polyimide as grids material. EWD devices that use poly(imide siloxane) as hydrophobic insulator fabricated with conventional methods showed good and reversible electrowetting performance on both single droplet level and device level, which showed its potential application in EWDs. The compatibility of polyimide-based materials (hydrophobic poly(imide siloxane) and hydrophilic polyimide) guarantee the good adhesion between two layers and the capability of printable fabrication. To this end, the hydrophilic grids have been successfully built on hydrophobic layer by screen-printing directly. The resulting EWD devices showed good switch performance and relatively high yield. Compared to conventional method, the polyimide-based materials and method offer the advantages of simple, cheap and fast fabrication, and are especially suitable for large area display fabrication.

1. Introduction

Many experimental and theoretical activities have recently been taken in the field of electrowetting, driven by applications in lab-on-a-chip [1,2], adaptive lens and prisms [3–5], and high-speed reflective displays [6,7]. The electrowetting concept for display application was first recognized by Beni and co-workers more than three decades ago [8–11]. The reflective display technology based on electrowetting was first realized and published in 2003 by Hayes and Feenstra at Philips Research Labs [6]. EWD has shown its potential for high quality information displays: (1) reflective mode for using ambient light and energy-saving; (2) quick response (<2 ms switching speed has been reached) for video display [12]; (3) good optical performance (>50% white state reflectance [13] and full color [14]); and (4) fluidic and soft display materials for flexible displays in the future.

Based on the classical theory of electrowetting, an electrostatically induced reduction of contact angle on the hydrophobic surface occurs when a voltage is applied between the conductive fluid and electrode underneath [15]. In the case of a sessile aqueous droplet on a hydrophobic insulating surface, the so-called electrowetting on dielectric occurs, as shown in Fig. 1a and b. It is considered that the voltage V only induces a change in the solid–liquid interfacial tension γ_{sl}; the interfacial tensions of solid–gas γ_{sg} and liquid–gas γ_{lg} are assumed to be unperturbed. The solid–liquid interfacial tension is reduced by an amount equal to the electrostatic energy $CV^2/2$, where C is the capacitance. As the electrode is covered by a hydrophobic insulating layer with thickness d and dielectric constant ε_r, this can be described by:

$$\cos\theta_v = \frac{\gamma_{sg} - \gamma_{sl}}{\gamma_{lg}} + \frac{1}{2}\frac{CV^2}{\gamma_{lg}} = \cos\theta_0 + \frac{\varepsilon_0\varepsilon_r}{2\gamma_{lg}d}V^2 \quad (1)$$

where θ_v and θ_0 are the contact angles of the liquid droplet with the applied voltage of V and 0, respectively. This equation has been successfully employed by many investigators in correlating experimental results with theory for a significant change of the contact angle.

The display principle is shown in Fig. 1c and d, utilizing a colored oil and transparent water dual fluidic system. In the absence of a voltage, the oil forms a continuous film in a pixel between the hydrophobic insulator-covered electrode and water due to the dominance of interfacial tensions: $\gamma_{ow} + \gamma_{oi} < \gamma_{wi}$, where γ_{ow}, γ_{oi} and γ_{wi} are the oil/water, oil/insulator and water/insulator interfacial tensions, respectively. When a voltage is applied between the top and bottom electrodes, the stacked state is no longer energetically favorable since an electrostatic force is added. Water moves

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http://dx.doi.org/10.1016/j.displa.2014.09.003
0141-9382/

towards the insulator, pushing the oil film aside or break. In this way, the optical properties of the stack, when viewed from the top, are tuned between a colored off-state (dyed oil) and a white on-state (color of bottom substrate). Thus a simple and highly reversible optical switch is obtained, driven by electrowetting.

As shown in Fig. 1c and d, the standard configuration of an EWD device consists of the bottom substrate with electrodes, a hydrophobic insulator layer, hydrophilic grids, colored oil and conductive liquid, and electrodes on the top substrate. The response of electrowetting effect highly depends on the properties of these materials. Particularly, the properties of the hydrophobic insulating layer are known to play a key role in EWD devices [2]. To obtain a wide contact angle change with low voltage, the high initial contact angle of the conductive liquid is preferred. To obtain both insulating and hydrophobic functions, multilayers have also been studied. Inorganic insulating materials like SiO_2 [2], Si_3N_4 [16], SiOC [16], or ONO (oxide-nitride-oxide) [17] have been investigated, combined with a hydrophobic coating layer. This offers a larger contact angle change at the same applied voltage due to their higher values of dielectric constant.

The most commonly used hydrophobic insulator coatings for EWD devices are amorphous fluoropolymers such as AF1600 from DuPont [6,18], FluoroPel 1601V from Cytonix [19,20] and Cytop CTL-809M from Asahi Glass [21]. The low surface tension and viscosity makes it possible to fabricate a homogeneous film by screen printing. We have successfully screen-printed commercial fluoropolymers as the EWD hydrophobic insulator layer (not published). However, these materials are relatively expensive, and not compatible with commonly hydrophilic grids. Therefore, sophisticated surface treatment has to be done: low power plasma treatment [20,22,23] or chemical etching [24]. The typical EWD fabrication process is shown in Fig. 2 where the surface plasma treatment and high-temperature recovery steps are critical and time-consuming. This also limits its applications in cheap and quick fabrication for industrialization. Currently, the hydrophilic grids are still fabricated using photolithography which again includes several steps: coating, pre-baking, exposing, post-baking and developing. Cheaper materials and simpler fabrication procedure are highly required for the technology development and industrialization.

Polyimide has the advantages of high thermal stability, good chemical resistance, good optical property and ease of processing, therefore has been widely applied in many high performance applications [25–28]. Among them, in poly(imide siloxane) the

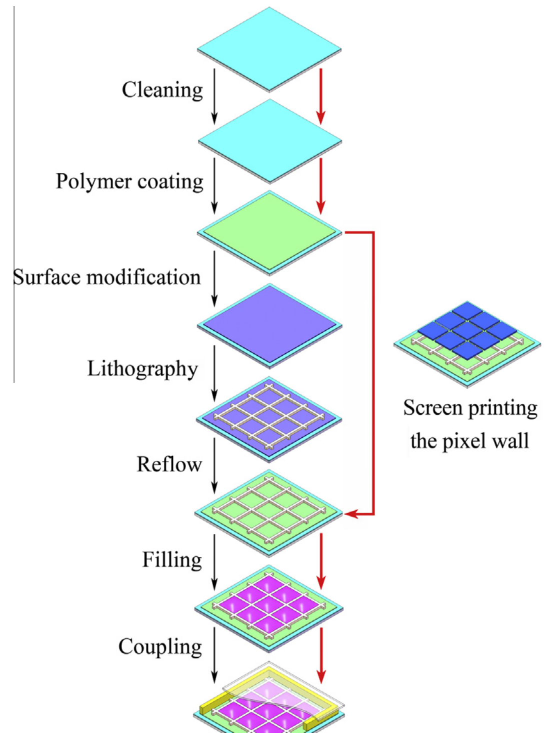

Fig. 2. Schematic process flow in the conventional fabrication and the proposed printing fabrication process. The black arrows indicate conventional fabrication process, and red arrows indicate the new fabrication process. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

polysiloxane component imparts a number of beneficial properties to the polymeric system, including high hydrophobicity, low surface energy, high flexibility, enhanced solubility, reduced water sorption and gas permeability, good thermal and ultraviolet stability [29–31]. These particular advantages render polysiloxane-modified polyimides an excellent candidate for hydrophobic insulator materials as part of EWD devices. Furthermore, the polyimide–polyimide adhesion mechanism has been investigated and proven previously [32,33]. Therefore, the hydrophilic polyimide with good

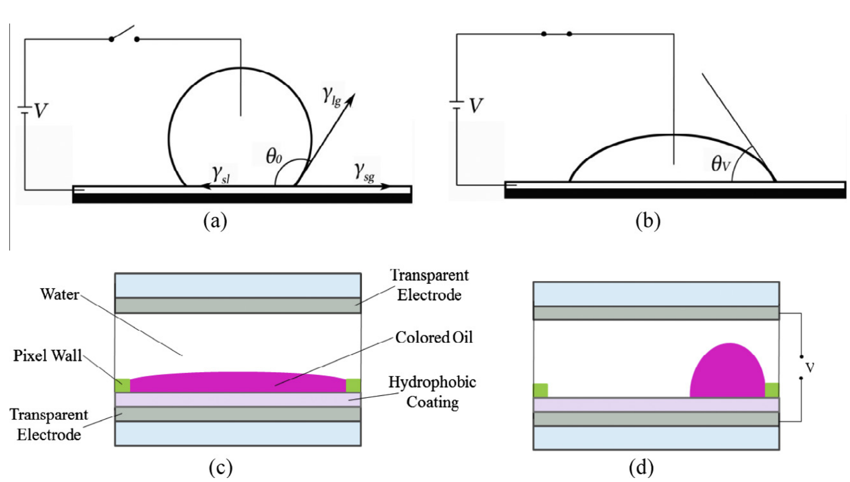

Fig. 1. Schematic illustration of droplet electrowetting and EWD performance. (a) Without voltage, the conductive droplet stands on the hydrophobic surface with a contact angle of θ_0. (b) With an applied voltage of V, the droplet spreads on the surface with a contact angle of θ_V. (c) In an EWD pixel, without applied voltage, a homogeneous oil film spreads over the pixel area showing the color of the dyed oil. (d) In an EWD pixel, with an applied voltage of V, the oil film contracts to one corner of the pixel, showing the color of the bottom substrate.