Fabrication of Lateral and Stacked Color Patterns through Selective Wettability for Display Applications

Jong-Ho Hong, Jun-Hee Na**, Hongmei Li**, and Sin-Doo Lee***

Abstract

A simple and versatile method of fabricating color patterns in two-dimension (2D) and three-dimension (3D) was developed using the selective-wettability approach. Red, green, and blue color elements are sequentially formed on a single substrate in a pattern-by-pattern and/or pattern-on-pattern fashion, through a simple coating process. Either 2D or 3D structures in an array format are produced by controlling the thickness of the hydrophobic layer (HL) coating a substrate within the framework of wetting transition. Moreover, it was demonstrated that the stacked geometry of two successive patterns can be easily tailored for various types of color arrays, with the pattern fidelity of a few tens of nanometers in terms of only a parameter of the HL thickness.

Keywords: color patterns, selective wettability, hydrophobic layer, pattern fidelity, display applications

1. Introduction

A color pattern array consisting of red (R), green (G), and blue (B) elements is an essential component for constructing color images in many optoelectronic devices, such as liquid crystal displays (LCDs) and white organic light-emitting diodes (WOLEDs). For advanced color applications, it is very important to produce high-resolution color patterns over a large area in a cost-effective manner. Among the various existing fabrication techniques for constructing color filters [1-4], the pigment dispersion method [1] has been widely used for mass production due to its efficiency and reliability. Basically, this method relies on photolithography and the wet chemical-etching processes, thus resulting in a high color resist and solvent consumption, patterning complexity, and a relatively long production time. The inkjet printing approach [5, 6] was recently demonstrated as saving cost and time, but it still suffers from pattern infidelity and from the incompatibility of the ink solution with the printing nozzle.

In this work, a simple and versatile method of fabricating color patterns in two-dimension (2D) and three-dimension (3D) via selective-wetting inscription (SWI) was developed [7]. Different color elements are sequentially formed on a single substrate in a pattern-by-pattern and/or pattern-on-pattern fashion, through a simple coating process. The unit process is schematically illustrated in Fig. 1(a). First, a hydrophobic layer (HL) is prepared on a hydrophilic substrate by spin-coating. After laser-inscribing the HL through a photomask with predefined patterns, the substrate is dip-coated in color ink, and then the color patterns are formed

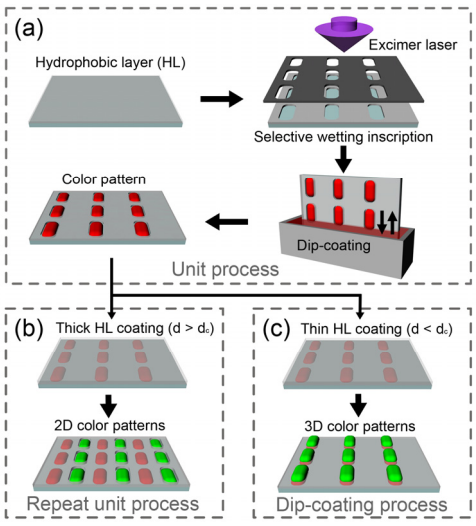

Fig. 1. Schematic illustration of the fabrication of multidimensional heterogeneous color patterns using SWI: (a) The unit process of producing red color patterns; (b) fabrication of red and green color patterns in 2D by repeating the unit process; and (c) fabrication of stacked green and red color patterns in 3D.

Manuscript Received November 08, 2010; Revised December 24, 2010; Accepted for publication December 24, 2010.
This work was supported in part by Samsung Mobile Display Co., Ltd. and Inter-university Semiconductor Research Center.
*Member, KIDS; **Student member, KIDS
Corresponding author: Sin-Doo Lee
School of Electrical Engineering, #032 Seoul National University, Kwanak P.O. Box 34, Seoul 151-600, Republic of Korea
E-mail: sidlee@plaza.snu.ac.kr **Tel:** +82-2-880-1772 **Fax:** +82-2-874-9769

only on the hydrophilic regions. By simply repeating this unit process, two-dimensional (2D) heterogeneous color patterns can be easily produced, as shown in Fig 1(b). Note that when the thickness of a subsequent HL is smaller than a certain value (a few tens of nanometers) at which critical wetting transition occurs, three-dimensional (3D) color patterns are produced without an additional SWI process, as shown in Fig 1(c). Depending on the thickness of the HL, either 2D lateral or 3D stacked structures can be constructed.

2. Experimental Consideration

A hydrophobic fluoropolymer (DS-1120, Harves Co., Ltd.) was spin-coated on a glass substrate and cured at 85°C for 30 min, for use as an HL. The thickness of the HL was varied from a few tens of nanometers to a few hundred nanometers, while varying the spinning rate and the concentration of the HL solution. The wetting properties of the HL were determined in terms of the contact angles of water and

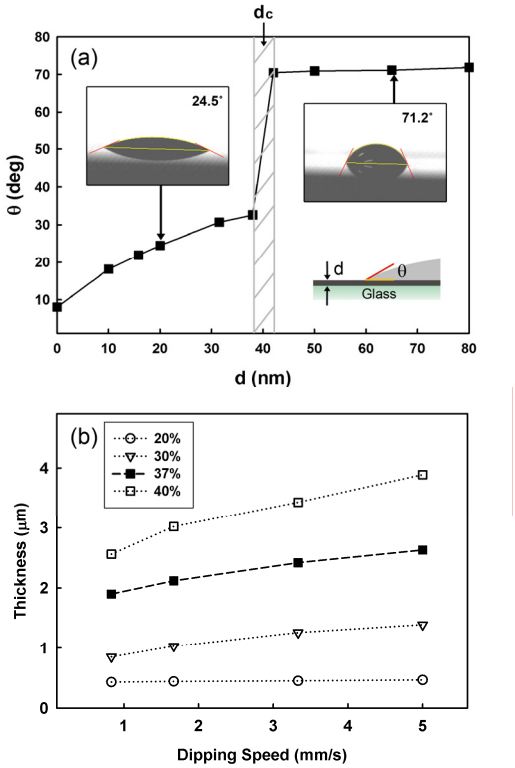

Fig 2. (a) Contact angle of the red color ink on the HL and (b) HL thickness as a function of the dipping speed for different concentrations of the red-color-ink solution. The hatched area in (a) represents the critical region where wetting transition occurs.

three pigment-based color inks (Dongwoo Fine-Chem Co., Ltd.), using a contact angle measuring system (Phoenix 300, Surface Electro Optics Co., Ltd.). The contact angle of water on the HL was 118°. Fig. 2(a) shows the change of the contact angle of the typical R ink as a function of HL thickness d. A schematic diagram representing a droplet in contact with the HL layer on the substrate and two examples of the contact angles are also shown in Fig. 2(a). Note that the HL is chemically inert to a color ink solution. The contact angle of the R color ink slightly increases up to 33° and then abruptly increases to about 70° at the critical thickness d_c≈40 nm. This indicates that a certain type of wetting transition occurs as a function of the HL thickness (see the hatched area in Fig. 2(a)) [8]. Similar to the previous work on polymer electroluminescent materials [7], it is suggested that heterogeneous color elements will be produced using the concept of such wetting transition observed in DS-1120. In the case herein, a 60-nm-thick (above d_c) HL was used to produce 2D lateral color patterns by repeating the SWI process in sequence. The use of two different HL thicknesses (16 and 32 nm) allows for 3D stacked color patterns.

To generate selective-wetting regions on a glass substrate, the HL was first inscribed with a KrF excimer laser (wavelength λ=248 nm, Lambda Physik) at the intensity of 10 J/cm^2, through a photomask with predefined patterns. During the inscription, the HL was selectively removed, and hydrophilic regions were prepared. The substrate was then dip-coated with color ink so that the color patterns would be spontaneously formed only on the hydrophilic regions. After the baking of the substrate, the geometric profiles of the color patterns were analyzed using a surface profilometer (Alpha-Step 500, KLA Tencor). In Fig. 2(b), the thickness of the R color pattern is shown as a function of the ink solution concentration. The thickness increases along with the ink concentration for a given dipping speed, which is consistent with the previous results [9]. The dependence of the thickness on the dipping speed is rather weak for a low ink solution concentration. About-2-μm-thick color patterns, typically used for color filters, were obtained at 37% ink concentration and at 1.7 mm/s dipping speed. The unit process for producing color patterns in either 2D or 3D was carried out under these conditions. The HL was finally removed by immersing the substrate in a weak fluorinated solvent, which would not disrupt the color patterns. In heterogeneous 3D color patterns, two HL thickness regimes (d_1=16 nm and d_2=32 nm) clearly distinguish between spon-

taneously stacked patterns and independently processed patterns. Two types of G-on-R patterns were fabricated to demonstrate the HL-thickness-dependent process.

3. Results and Discussion

A color array composed of three color patterns (R, B, and G) is shown in Fig. 3(a), which is the optical microscopic image of the R, B, and G patterns produced on a glass substrate. The width and length of each pattern were 120 and 350 μm, respectively. Fig. 3(b) shows the geometric profile of a set of RGB patterns. Each color pattern was well defined in a 50-μm-separated convex shape. Note that the thickness and geometric shape depend on the viscosity and evaporation rate of the color ink used. Under the fabrication conditions, the average thicknesses of the R, G, and B patterns were determined to be about 3, 2.2, and 2.2 μm, respectively. The transmittance spectra of the 2.2-μm-thick RGB color patterns are shown in Fig. 3(c). The transmittance of the B patterns at the wavelength of 450 nm was about 70%, that of the G patterns at 530 nm was slightly higher than 70%, and that of the R patterns at 640 nm was over 80%. It should be emphasized that the selective-wetting method is not limited to color inks but is applicable to a wide range of soluble functional materials and colloidal dispersions [10, 11].

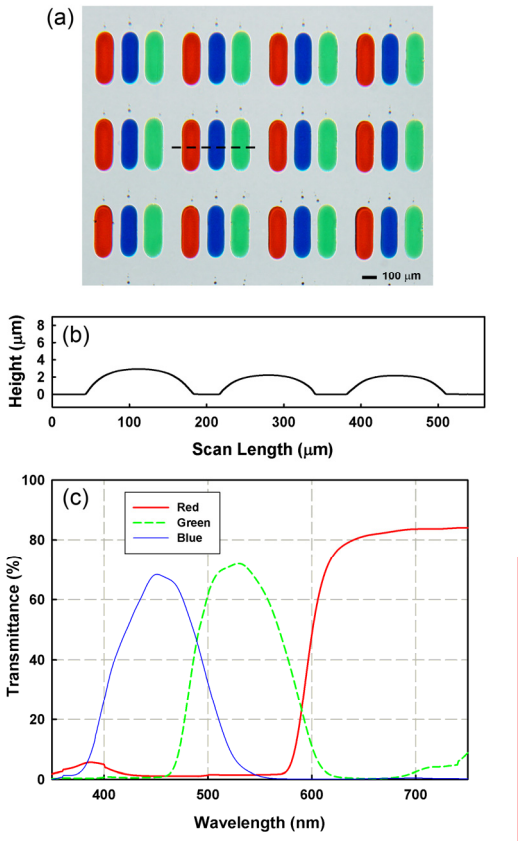

Fig. 3. RGB color array fabricated on a glass substrate through sequential unit processes: (a) optical-microscopic image of RGB color patterns; (b) geometric profile of a set of RGB color patterns; and (c) transmittance spectra of 2.2-μm-thick RGB color patterns.

How different forms of color patterns can be stacked in a pattern-on-pattern (3D) fashion depending on the HL thickness below d_c will now be described. Two HLs, one much smaller than d_c and the other close to d_c, were used. More specifically, d_1 = 16 nm and d_2 = 32 nm were chosen to distinguish between the entirely covered and partially covered patterns in 3D. In the first type of G-on-R patterns, G patterns were found to cover the whole R patterns (180 μm in diameter) when the HL thickness was 16 nm, as shown in Fig. 4(a). As shown in Fig. 4(b), however, for the 32-nm-thick HL, the second type, where small G patterns (50 μm in diameter) were produced in the center regions of large R patterns (180 μm in diameter), was obtained. This is suggested from the fact that long-range Van der Waals forces in the hydrophilic regions propagate through the HL when the HL is much smaller than a certain critical thickness [12]. In the case herein, the critical thickness d_c is about 40 nm, and the contact angle decreases exponentially as the HL thickness decreases [13]. Note that the excess coverage of the G patterns over the R patterns in Fig. 4(a) depends on the amount of the G ink solution dip-coated on the HL and the

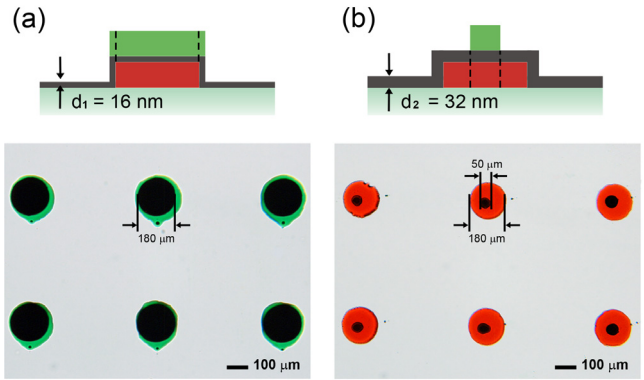

Fig. 4. Two types of G-patterns-on-R-patterns depending on the HL thickness: (a) whole coverage of the G patterns over the R patterns for the HL of d_1=16 nm; and (b) partial coverage of the G patterns in the center regions of the R patterns for the HL of d_2=32 nm.

evaporation rate of the ink solution.

4. Conclusion

A new method of fabricating multidimensional color patterns using the selective-wetting process was developed within the framework of wetting transition in terms of the HL thickness. High-fidelity color arrays composed of lateral patterns in 2D and/or stacked patterns in 3D can be sequentially produced via simple dip-coating, which is applicable to large-area coverage at a low cost. In different classes of chromatic materials, the approach described herein will provide a new platform for developing a variety of color-coding components necessary for high-performance opto-electronic and photonic systems.

References

[1] K. Takanori, N. Yuki, N. Yuko, Y. Hidemasa, W. B. Kang, and P. G. Pawlowski, *Jpn. J. Appl. Phys*. **37**, 1010 (1998).

[2] T.-M. Lee, Y.-J. Choi, S.-Y. Nam, C.-W. You, D.-Y. Na, H.-C. Choi, D.-Y. Shin, K.-Y. Kim, and K.-I. Jung, *Thin Solid Films* **516**, 7875 (2008).

[3] T. Sugiura, *J. Soc. Inf. Disp.* **1**, 177 (1993).

[4] M. Suginoya, H. Kamamori, K. Iwasa, M. Kai, T. Nomura, J. Yasukawa, and T. Suzuki, *SID Int. Symp. Dig. Tech. Pap.*, p.115 (1987).

[5] P. Calvert, *Chem. Mater*. **13**, 3299 (2001).

[6] H.-S. Koo, P.-C. Pan, and T. Kawai, *Appl. Phys. Lett.* **88**, 111908 (2006).

[7] Y.-J. Na, S.-W. Lee, W. Choi, S.-J. Kim, and S.-D. Lee, Adv. Mater. **21**, 537 (2008).

[8] W. A. Zisman, *Adv. Chem.* **43**, 1 (1964).

[9] A. A. Darhuber, S. M. Troian, J. M. Davis and S. M. Miller, *J. Appl. Phys*. **88**, 5119 (2000).

[10] Y. D. Kim, J. P. Kim, O. S. Kwon, and I. H. Cho, *Dyes and Pigments* **81**, 25 (2009).

[11] S.-K. Lee, G.-R Yi, J. H. Moon, S.-M Yang, and D. J. Pine, *Adv. Mater.* **18**, 2221 (2006).

[12] G. Reiter, A. Sharma, A. Casoli, M.-O. David, R. Khanna, P. Auroy, *Europhys. Lett*. **46**, 512 (1999).

[13] C. W. Extrand, *Langmuir* **9**, 475 (1993).