Ring-Edged Bank Array Made by Inkjet Printing for Color Filters

Jhih-Ping Lu, Fang-Chung Chen, and Yuh-Zheng Lee

***Abstract*—A mask-free inkjet printing (IJP) process has been developed to fabricate color filters. The coffee ring effect was used to create a ring-edged bank array with fine structures by IJP of poly(methylmethacrylate). After the color filtering inks were deposited in the banks, a color filter panel was made without any transitional photolithography process. The resulting color coordinates of the three primary colors on the chromaticity diagram are (0.70, 0.30), (0.33, 0.60) and (0.14, 0.09), respectively, covering 67.8% of the National Television System Committee standard. This process can be used with flexible substrates to produce low-cost inkjet printed color filters.**

***Index Terms*—Inkjet printing (IJP), color, optical arrays, thin films.**

I. Introduction

INKJET PRINTING (IJP) has been recognized as a promising tool for mass production in the display industry because of its simplicity, low cost, flexibility and maturity [1]–[3]. Potential applications, such as the fabrication of polymer light-emitting diode displays and color filters for liquid crystal displays, have been reported [4]–[8]. However, to prevent the inks in subpixels from color mixing, bank structures must be established using conventional photolithography before the printing process. Although the band structure could be fabricated by IJP as well, the resulting structure is usually too large for applications in high-resolution displays.

During the printing processes, the coffee ring effect, a natural phenomenon that occurs when a solution dries into a solid film [9]–[14], is commonly observed. Because the perimeter of the droplet on the substrate dries rapidly, a pinned contact line is usually formed. Once the edge is pinned, surface tension will induce a capillary flow from the interior to the edge of the droplet, solvent evaporating at the edge is replenished from liquid at the edge. Hence, a thicker, narrower perimeter is formed after the solution has dried. Because of the buildup of solute at the edge, coffee ring effect always results in a thin film with a rough surface. On the other hand, the coffee ring effect potentially can be used to produce fine lines or a microstructure pattern [15], [16]. In this work, we demonstrate such an example, in which the coffee ring effect is used to fabricate a ring-edged bank array (REBA). The bank structure could be easily realized by inkjet printing of inert polymers. After the color filtering inks was deposited in the banks, a color filter panel was made without any transitional photolithography process.

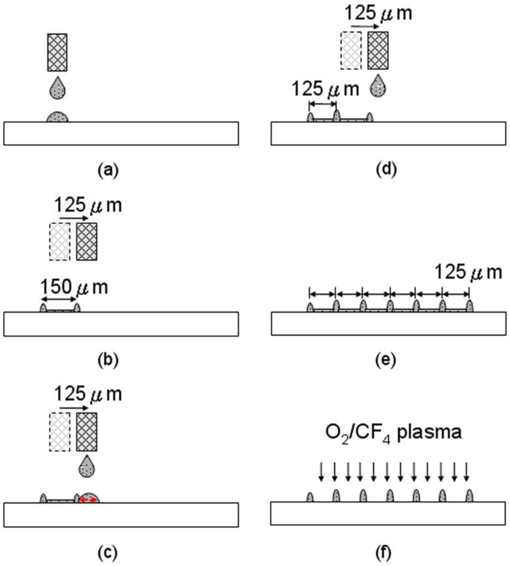

Fig. 1. Process flow of the printing method in this study: (a) The solution droplet was deposited onto a flat surface of the substrate. (b) The first droplet became a 150-μm trench and the printhead shifted perpendicularly to the trench by 125 μm. (c) The second droplet redissolve the lateral ridge of the first trench; (d) The width of the first trench decreased to 125 μm because the second droplet redissolved the edge of the first one. Then, the printhead shifted perpendicularly to the trench by 125 μm continuously. (e) An array with 125 μm pitch formed. (f) Oxygen plasma was used to etch the polymer until the thinner part was removed completed. CF_4 plasma was further applied to modify the surface of the ridges.

II. Experimental

Fig. 1 illustrates the overall procedures for fabricating a bank array by inkjet printing. Based on Deegan's principle [14], the viscosity and volatility characteristics of the solution affect the profile of a ring-shaped edge. Our results indicated that a more viscous solution or a higher boiling point solvent is associated with the formation of a wider ring ridge [16]. Accordingly, given that the nozzle must not be clogged, a low concentration and a solvent with a moderate boiling are critical parameters to obtaining a fine ring-edged ridge. Therefore, poly(methylmethacrylate) (PMMA) was dissolved in anisole at a concentration of 0.8 wt%. After filtering through a 0.45-μm

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filter, an IJP system with thermal bubble printhead, equipped in Industrial Technology Research Institute, was employed to print the REBA and color inks. The print head contains fifty nozzles and the average drop volume was 30 pl. Using only one of the nozzles, the PMMA solution was printed in a straight line on bare, clean glass substrates [see Fig. 1(a)]. The printed line width was 150 μm at a dot printing density of 60 μm/drop. As the thin films had dried, a rail-like pattern with a 150 μm-wide trench immediately formed within 2 seconds following the coffee ring effect [Fig. 1(b)]. Then, the printhead was sequentially shifted perpendicularly to the rail-like patterns by 125 μm to print the second line as shown in Fig. 1(b) and (c). Because the printed lines partially overlapped with each other, the second line redissolved the lateral ridge of the first trench and a new one was formed [see Fig. 1(d)]. The width of the new trench equaled to the distance through which the printhead shifted was 125 μm. Repeats of this pattering method yielded a micro bank array with the same interval, 125 μm [see Fig. 1(e)]. After the formation of the array pattern, further ion-coupled plasma treatment was conducted to etch the thin film and to make the remained ridge surface ink-repelling [Fig. 1(f)]. The thinner part was fully removed using O_2 plasma for a period of 30 s at an etching rate of 6.8 Å/s. The remained ridge was then treated with CF_4 plasma for 100 s at a small etching rate of 0.3 Å/s to modify the surface. Finally, when inks of color filters were deposited in the trenches, the color filter array was completed. In this process, we observed that the ridges were not dissolved by the color inks. We suspect that that the vacuum environment had made the ridges dried in the CF_4/O_2 plasma process. Further, the repellent surface of ridge induced after the CF_4 plasma-treatment also prevents the ridge being dissolved by the color inks. Since the pitch size of the banks equaled to the distance through which the printhead shifted, any sizes of bank pitch can be obtained merely by controlling the position of the printhead. The color filter solutions, dissolved in propylene glycol monomethyl ether acetate, were obtained from AGI Corp. After the bank array with a sub-pixel pitch of 125 μm was established using the aforementioned method, a 35-pl piezoelectric printhead was adopted to print the color filter solutions. By controlling the dot printing density, proper thicknesses could be obtained. The REBA profile was obtained using the SNU SIS-1200 profile meter. The RGB chromaticity coordinates were measured using a Photal MCPD-3000 Spectro Multichannel Photodetector.

III. RESULTS

Fig. 2 shows the image of a REBA obtained using an optical microscopy and its profile acquired from an interferometer profile. The average width, height and pitch size of the band structure were approximately 15.00, 0.50, and 123.45 μm, respectively. It is worthy to note that the resulting length of trench was indeed closed to the shifting distance (125 μm) of the printhead. Therefore, the experiment results prove that pitch size of the bank array is equal to the distance through which the printhead shifted.

The as-made REBA was subsequently applied to fabricate a color filter panel. Fig. 3(a) presents the optical microscopic images of the red color film at dot printing densities of 100, 60, 40, and 30 μm/dot, respectively. Generally, a higher printing density corresponds to a thicker color resist. However, as shown in Fig. 3(a) and (d), improper dot printing densities resulted in

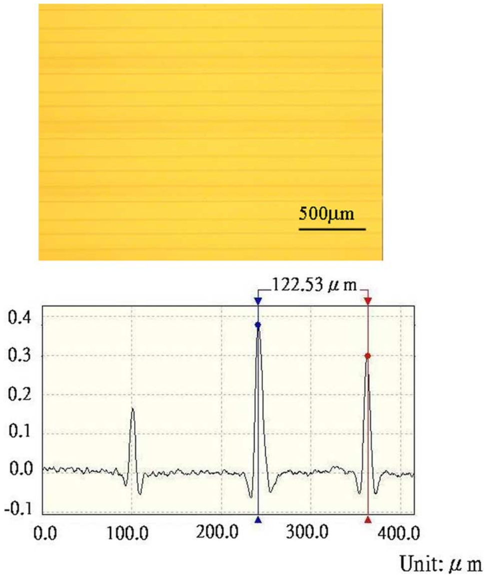


Fig. 2. (a) Image of a micro bank array obtained from an optical microscopy and (b) its profile acquired using an interferometer.

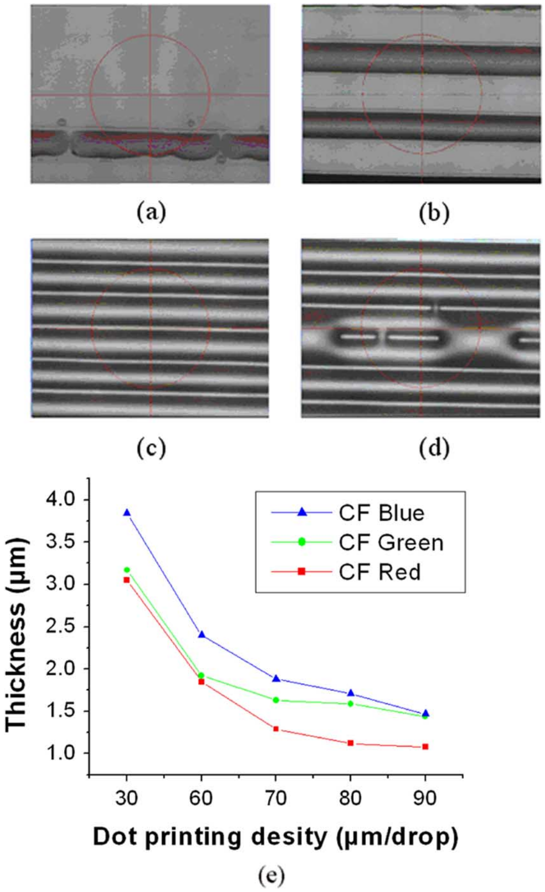
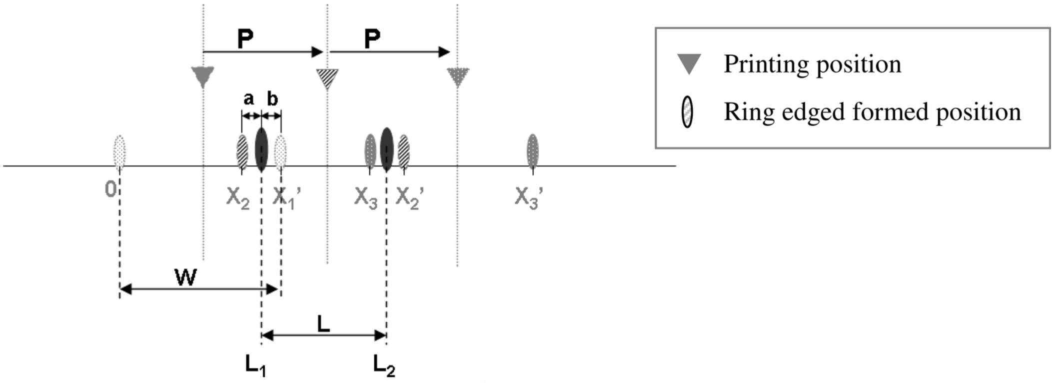


Fig. 3. Optical images of the color filters with different dot printing density: (a) 0.010 μm^{-1}; (b) 0.017 μm^{-1}; (c) 0.025 μm^{-1}; (d) 0.033 μm^{-1}; The corresponding dot-to-dot distant were: (a) 100 μm; (b) 60 μm; (c) 40 μm; (d) 30 μm, respectively. (e) The relationship between the film thickness and the dot printing density for the resist with different colors.



Graphic 1.

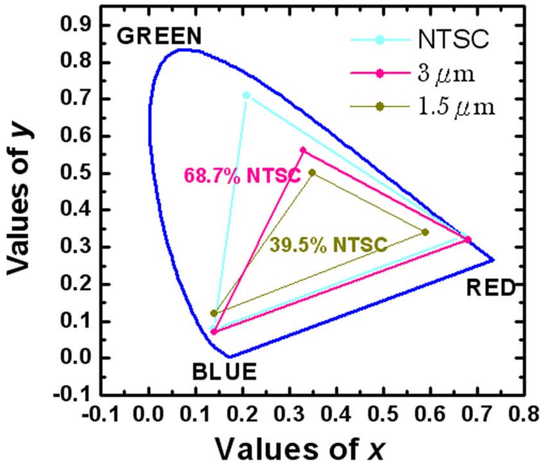


Fig. 4. Chromatic diagram of the color filter panel made in this study.

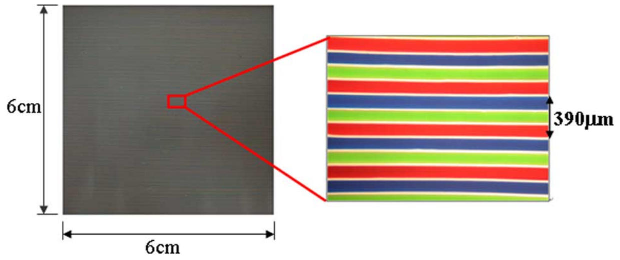


Fig. 5. Optical microscopy photograph of a color filter panel fabricated by the all-IJP approach.

discontinuities or overflow defects. On the other hand, better film quality was obtained while a moderate density was used. The thicknesses were 1.89 and 3.03 μm, respectively, for the films printed with dots pitch of 40 and 60 μm/dot, respectively, as shown in Fig. 3(b) and (c). Fig. 3(e) plots the relationship between the film thickness and the inverse of the dot printing density. The results revealed that the thickness of each colored film can be predicted and easily controlled from 1 to 3 μm by simply tuning the dot printing density.

The quality of the color filters with various film thicknesses was further characterized by measuring the color coordinates. As shown in Fig. 4, the colored region of the printed RGB color filters ($\sim$3 μm) covered approximately 67.8% of the National Television System Committee (NTSC) standard. The coordinates of the red, green, and blue filters on the chromaticity diagram were (0.70, 0.30), (0.33, 0.60), and (0.14, 0.09), respectively. Fig. 5 shows the optical microscopic photograph of the color filters. The printing area was 6×6 cm^2 and the sub-pixel pitch was 125 μm. The thickness of each RGB resist film was about 2.5 μm at a dots printing pitch of 50 μm/dot. The resulting color filter array did not have any color-mixing due to either overflow, splash or satellite drops.

IV. CONCLUSION

In conclusion, a method for easily and controllable fabrication of a micro-bank array has been established. This bank forming approach can not only replace convention photolithography, but also can pattern any pitch of bank that is equivalent to the distance through which the printhead shifted. In other words, the parameters can be easily turned. Additionally, highly saturated color filters fabricated by all-IJP processes have been demonstrated. The thickness of the RGB color films can be fine-tuned by varying the dot printing density; a thickness of 1–3 μm in single-swath printing was achieved without any color-mixing. The color region of the three primary colors (red, green, and blue) on the chromaticity diagram reaches 67.8% of the NTSC standard. The color filters could be used for liquid crystal displays, image sensors, and other colored devices.

APPENDIX

To prove the equivalency of the trench width and the distance through which the printhead shifted, the printing process is described mathematically, as shown in Graphic 1.

The trench width of each printed line is “W”; the distance through which the printhead shifted is “P”, and the resulting ridge pitch is “L”.

Therefore

$$\overline{OX_1}' = W$$
$$\overline{OX_2} = \left(\frac{w}{2}\right) + P - \left(\frac{w}{2}\right) = P.$$

Assume that “L_1” is located along the line between X_2 and X_1' at a distance of fraction $[\mathrm{a}/(\mathrm{a}+\mathrm{b})]$ from X_2 Then,

$$L_1 = \left(\frac{a}{a+b}\right) \cdot (\overline{OX_1}' - \overline{OX_2}) + \overline{OX_2}$$

$$
\begin{aligned}
&= \left(\frac{a}{a+b}\right)\cdot(W-P)+P\\
\overline{OX_2}' &= \overline{OX_2}+W = P+W\\
\overline{OX_3} &= \left(\frac{w}{2}\right)+P+P-\left(\frac{w}{2}\right) = 2P.
\end{aligned}
$$

Assume that "LL_2 " is located along the line between X_3 and X_2' at a distance of fraction $[a/(a+b)]$ from X_3 Then

$$
\begin{aligned}
L_2 &= \left(\frac{a}{a+b}\right)\cdot\left(\overline{OX_2}'-\overline{OX_3}\right)+\overline{OX_3}\\
&= \left(\frac{a}{a+b}\right)\cdot(P+W-2P)+2P\\
\therefore L = L_2-L_1 &= \left(\frac{a}{a+b}\right)\cdot(P+W-2P)\\
&\quad +2P-\left(\frac{a}{a+b}\right)\cdot(W-P)-P\\
&= 2P-P = P.
\end{aligned}
$$

The ridge pitch "L" is derived to equal to the distance through which the printhead is shifted "P".

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