Monochrome and Area Color Microcup® EPDs by Roll-to-Roll Manufacturing processes

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Abstract

Bistable electrophoretic displays (EPDs) are one of the most encouraging technologies for electronic paper applications due to their advantages in ultra-low power consumption, flexibility, light weight, wide viewing angle, and reflective contrast. Monochrome Microcup® EPDs are produced by roll-to-roll manufacturing at high throughput via microembossing, continuous filling, and seamless sealing processes on plastic substrates. The innovative filling and sealing process is the key for roll-to-roll manufacturing. SiPix Microcup® arrays not only provide partitions to enhance dispersion stability of the electrophoretic fluid and offer excellent physicomechanical properties to the display structure, but they also enable color separation such that electrophoretic fluid of different color may be individually filled and sealed into a predetermined set of microcups. Color gamut of a dual-mode electrophoresis display is estimated through simulation to show the potential of a full color reflective display. Vivid area color Microcup® EPDs are demonstrated for direct drive POP signs.

Introduction

In the display industry, the pursuit of an ultra-light electronic display system with low power consumption and decent display performances has been going on for decades[1]. Such displays would penetrate the market that has been dominated by paper and printing since the beginning of information sharing by mankind. Various bistable displays, which can hold images without continuing to supply power, have been investigated for the obvious reason of low power consumption. Among them, electrophoretic displays (EPDs) have been considered among the most promising approaches and have been improved and optimized in recent years. Contrast is achieved by migration of charged colored particles inside fluid of different color or migration of two particles of different color and charge in a colorless fluid. Its reflective feature gives a comfortable visual effect under various light conditions. EPDs can be highly flexible. Even if flexibility is not the required feature for the final display, being flexible opens up opportunities for efficient, high throughput web processing. The field driven mechanism of EPD makes it less demanding for backplane mobility performance, which ensures good compatibility with developing flexible active matrix backplane technologies. This feature will contribute to its ultra-light weight and efficient integration. SiPix first demonstrated passive matrix EPD with enough intrinsic threshold to overcome the undesirable cross-bias among adjacent pixels during matrix driving, which is a less expensive electrode structure than active matrix driving for complex image displays[2, 3].

Monochrome color bistable displays find a range of applications in handheld devices, such as e-books and PDAs, and electronics signage and labels. Area color and full color displays are more attractive especially in retail market. Color provides added value to POP signs and play an important roll in buying decision. SiPix provides solutions for roll to roll manufacturing of monochrome, area color and full color Microcup® EPDs.

Roll-to-roll manufacturing processes and material requirements

Roll-to-roll manufacturing processes based on novel Microcup® structure and top sealing technology was developed in SiPix Imaging Inc. using conventional coating and printing facilities[2, 4]. Figure 1 showed a schematic structure of SiPix Microcup® EPD, which adopts single particle colored dispersion. The active display material, electrophoretic dispersion, is enclosed inside microcup® arrays to prevent material migration to achieve good image uniformity. Ultra-thin, ultra-light, flexible electrophoretic films with excellent display performances were manufactured on a continuous web at high throughput.

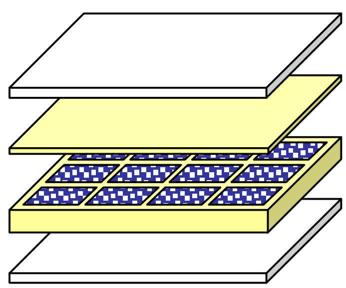
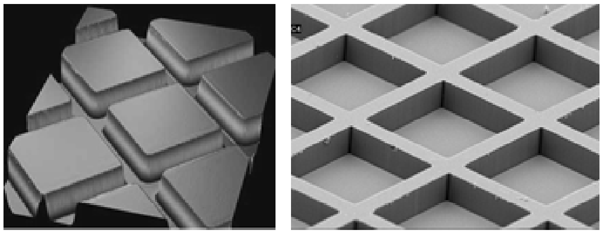


Figure 1. *Schematic structure of SiPix Microcup® EPD*

SiPix Microcup® and continuous microembossing

The Microcup® array works as partitions to uniformly distribute the electrophoretic dispersion over the whole display regardless the settling of the particles inside the electrophoretic fluid. It provides excellent structural support for the display, such that the EP films are flexible, durable and with consistent thickness. It also allows the EP film to be format flexible, so that from a standard roll of film, displays of different size can be produced.

The Microcup® array is manufactured through soft embossing using a metal embossing roller. The high quality embossing mold was fabricated via LIGA processes based on photolithography and electroplating technologies. Figure 2 illustrates a surface profile of the embossing mold and the corresponding microcup® array. A UV curable microcup® composition was coated on an ITO/PET web, as shown in previous publications[2], followed by embossing and hardening of the composition by radiation.



(2a) (2b)

Figure 2. Surface profiles of the embossing mold and the microcup® array: (2a) Surface of a metal embossing roller measured by Wyko surface profiler; (2b) SEM picture of a typical embossed microcup® with cup dimension of 100um in width and 20um in depth.

During the embossing process, there is always a thin layer of microcup® material between the top of the mold and the web substrate. This thin layer becomes the microcup® bottom, which works as an electrode protecting layer. This is different from the alternative photolithography method, which usually creates bottomless microcup® arrays. The microcup® formulation is comprised of multi-functional acrylate monomers and oligomers carefully selected for optimum rheology and fluid mechanics before curing and good mold releasing and physico-mechanical properties after curing. Additives, such as release agents, binders, anti-oxidents, UV protector, rheology modifier, and conductive filler can be incorporated into the formulation.

SiPix filling and seamless sealing technologies

Novel filling and top sealing technology is critical for roll-to-roll manufacturing. The dispersion fluid has a significant low surface tension due to its non-polar chemical nature. Top-coating a sealing material of higher surface tension with good adhesion to the microcup walls was previously considered theoretically unachievable. However, with careful material and solvent system selection to meet density, compatibility, and rheology criteria, seamless sealing with good adhesion is performed consistently on conventional coaters.

Formulations of microcup and sealing not only have to be compatible with the manufacturing processes, but they also have to meet the electrical criteria for better EPD performance. Each dielectric layer in the path of the electrical field may reduce the effective voltage on the active display material if the dielectric layer has a higher electrical resistance than that of the EP fluid. The high resistance dielectric layer also contributes to the reverse bias phenomenon, in which the EP dispersion will experience a reverse electric field when the driving voltage drops to zero after image update. However, if the resistance of the dielectric layer is too low, cross talk among pixels takes place. Fine-tuning the electrical resistance of each dielectric layer becomes crucial for EPD performance.

Monochrome Color Microcup® EPD

Monochrome color Microcup® EPDs are integrated by filling the microcups® with a particular color of electrophoretic dispersion. The monochrome color Microcup® EPDs currently available are black/white, green/white, blue/white, red/white, and gold/white. To enhance the contrast of the Microcup® EPDs, a colored layer may be used at one side of the microcup that is opposite to the viewer in order to compensate the light effect of the inactive microcup walls. Color may also be printed on top of the microcup wall at the viewer's side for the same purpose. The colored layer can be color matched to the color of the EP fluid or can be tuned to be different to achieve optimal contrast, color tint and reflectance. Pictures in figure 3 show several monochrome microcup® EPDs with good color saturation and decent contrast.

Figure 3. Monochrome Microcup® EPDs

Area color Microcup® EPD

Area color can be achieved by filling electrophoretic dispersions of different colors in the microcup® array at designated areas. EP fluid may be metered into the microcup by conventional printing methods or by strip coating, followed by top sealing. Figure 4 shows the configuration of a red and blue area color Microcup® EPD.

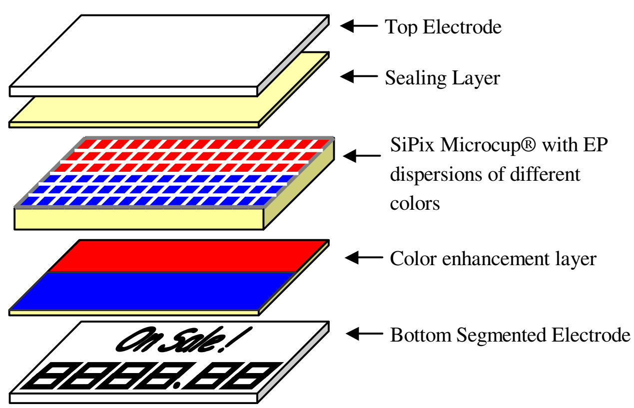


Figure 4. Area color Microcup ® EPD

A color enhancement layer that is made up of areas of highly reflective colors may be placed underneath the Microcup® layer to modulate the light that is transmitted through the transparent microcup walls. Alignment of the color enhancement layer and the Microcup® layer is needed. Contrast and color saturation can be significantly improved. The color enhancement layer may be printed directly on top of the backplane or may be printed on a release substrate and laminated onto the backplane. Figure 5 shows a three color Microcup® EPD module.

Figure 5. *A three color microcup® EPD module*

Full color Microcup® EPD by dual mode

The challenge of the up and down switching is the reproduction of black color. Each microcup can only show either the color of the white particle or one of the primary colors from the fluid. The dark state configuration is the horizontal arrangement of R, G, B colors with black matrix separating them. Light leakage is significant in its dark state. Color saturation and color gamut can be significantly improved by dual mode switching, as shown in Figure 6.

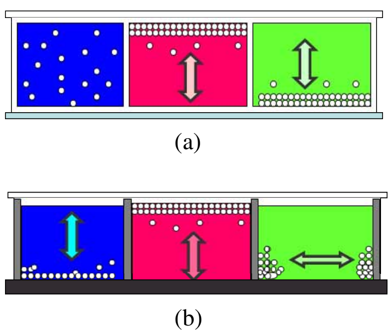


Figure 6. *Two switching modes: (a) up-and-down switching; (b) Dual mode switching.*

With dual mode switching is a combination of up-and-down switching and in-plane switching. Each microcup can show white, black and a primary color. The particles can move to the top to reproduce white. When they move to the bottom, it will reflect the light that is transmitted through the colored fluid. By incorporating another set of electrodes on the bottom or inside the microcup walls, particle can move horizontally to occupy the sidewalls, while the exposed black background will absorb all the light that is transmitted through the colored fluid. Assuming there is no light scattering in the colored fluid, true black can be reproduced. The comparison of the two switching modes is showed in Table 1.

The distribution of the particles along the wall after in-plane switching makes color viewing angle dependent. The color gamut will decrease with increase of viewing angle in reference to the normal plane. An easy approach to minimize the viewing angle sensitivity is to increase the fill factor. However, this will in turn either reduce the resolution or compromise the mechanical properties of the microcup structure. This problem can be solved by printing a black matrix on top of the mcirocup® walls or by making microcups with opaque and dark walls as shown in Figure 6 (b). Pigments and dyes can be incorporated into the microcup formulation to form the dark wall. It is critical to formulate an efficient initiator system under the light screening of the pigments or the dyes.

Table 1. Comparison of color performance of up-and-down switching and dual mode switching.

Color	Up-and-down switching	Dual mode switching
White	Good	Good
Black	Significant light leakage	Good, true black
Red	Washed out by adjacent white pixels	Better color saturation
Green	Same as above	Same as above
Blue	Same as above	Same as above

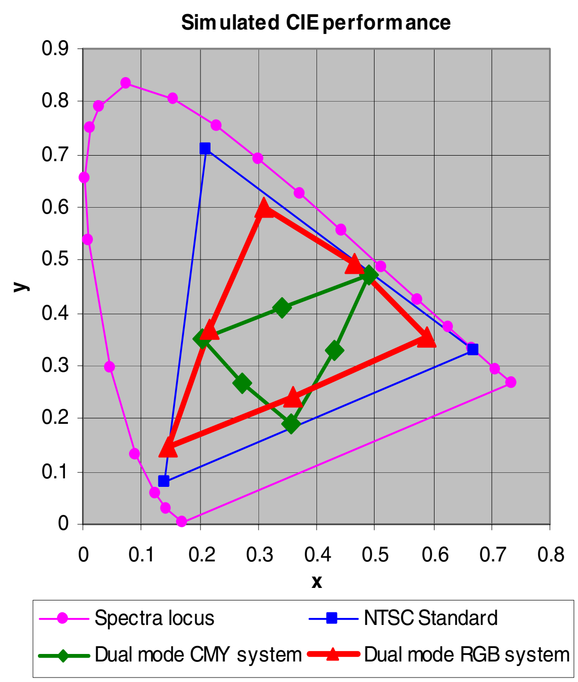


Figure 7. *Simulation on color saturation of dual mode switching*

The two primary color systems, subtractive colors and additive colors are used for different systems. Subtractive colors are used in reflective printing systems where staggering of the three colors is allowed, while additive colors are used in transmissive and emissive displays. Selection of primary color system will be important to achieve the optimal color gamut for reflective microcup® display with side by side arrangement of the primary colors. A simulation was performed using standard primary color spectra assuming an area of 26.67% for each primary color and 20% for black matrix occupying the top of the microcup walls. Figure 7 shows simulated CIE performance of a dual mode CMY system and a dual mode RGB system assuming D50 illuminator and observer at 2 degree.

In comparison to the NTSC standard, color saturation of 55% for the RGB system and 20% for the CMY system were obtained. Color saturation of red, green and blue is extremely low in the CMY system, because their spectra showed very high baseline reflection. RGB dual mode microcup ® EPD also has better color saturation than black and white EPD with color filters, in which white reflectance is significantly cut down by the color filter.

Summary

Monochrome color Microcup® EPDs are manufactured by roll-to-roll processes at high throughput. SiPix also provides solutions for area color and full color microcup® EPDs. Vivid area color microcup® EPDs were integrated by using multiple colored electrophoretic dispersions with a patterned color enhancement layer underneath. Dual mode full color Microcup® EPDs are simulated. A decent color gamut is achievable using RGB primary color dispersions.

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Author Biography

HongMei Zang received her PhD degree in Photochemical Sciences from the center for Photochemical Sciences at Bowling Green State University, Ohio, in 2000. After joining SiPix Imaging Inc,.she has been working on the development of sealing processes, and EPD dielectric material optimizations.

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Haiyan Gu received her BS in polymer chemistry from Nan Kai University in Tianjin, China (1995) and her PhD in photochemistry from Bowling Green State University (2001). Since then she has worked in the Research and Development Division at SiPix Imaging, Inc. Her work has focused on the improvement of the performances of electrophoretic display.

Yajuan Chen received her PhD in Chemistry department from University of Michigan in 1999. She joined Sipix Imaging inc. in 2000 and worked on the integration of electrophoretic displays.