

Microcup Electrophoretic Displays by Roll-to-Roll Manufacturing Processes

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ABSTRACT

Rolls of flexible electrophoretic displays (EPDs) have been prepared by a roll-to-roll manufacturing process based on novel Microcup and sealing technologies. The Microcup EPDs have shown outstanding performances in contrast ratio, response time, power consumption, image bi-stability, environmental stability, and physico-mechanical properties. The roll of displays may be cut into any size and shape for a variety of display applications without degrading the performance. The Microcup structure and processes significantly improve the performance and dramatically reduce the manufacturing cost. Passive matrix Microcup EPDs having threshold voltages ranging from 5-50V have been demonstrated for various applications.

INTRODUCTION

A flexible and durable reflective display with low power consumption, high contrast ratio, fast response time, thin and lightweight, and low manufacturing cost has been pursued for many years for various applications such as cellular phones, PDAs, e-sign and e-book. Among several other reflective display technologies, electrophoretic display (EPD or EPID) is known to be one of the most promising technologies and has been actively investigated in the past few years. Traditional EPDs has been proposed since 1969⁽¹⁻⁵⁾. Several new approaches, such as microencapsulated EPDs⁽⁶⁻⁸⁾, In-Plane EPDs^(9,10) and Reverse Emulsion EPDs⁽¹¹⁾, have been disclosed for improvements particularly in substrate flexibility and potential cost reduction. However, until now, no EPD technology in the prior art is capable of delivering all the display features and cost structure required to achieve any significant business success. In this paper, a revolutionary roll-to-roll EPD manufacturing process based on novel Microcup and sealing technologies⁽¹²⁻¹⁴⁾ (Figure 1-3) is disclosed. Ultra thin, ultra light, durable and flexible EPDs with excellent format flexibility and many desirable display features have been demonstrated and manufactured at a very low cost. Passive matrix Microcup EPDs having threshold

voltages ranging from 5-50V have also been demonstrated for a variety of applications.

MICROCUPS AND ROLL-TO-ROLL MANUFACTURING PROCESS

As it can be seen in the schematic drawing of a typical Microcup EPD (Figure 1), an electrophoretic fluid comprising charged pigment (TiO_2) microparticles dispersed in a colored dielectric solvent is enclosed and seamlessly sealed in the Microcups. Depending on the application, typical dimension of the Microcups may vary in the range of $60\text{-}180\mu\text{m}$ (w or l) x $20\text{-}40\mu\text{m}$ (h) x $10\text{-}30\mu\text{m}$ (ww). The Microcup array may be prepared by a lithographic or embossing process. A schematic process flow of a typical SiPix roll-to-roll EPD manufacturing process is shown in Figure 2. For example, rolls of Microcup EPDs have been prepared by (1) coating a radiation curable resin composition on a conductor film, (2) embossing and hardening the resin composition, (3) filling the Microcups with an electrophoretic fluid and sealing the filled Microcups with a sealing layer, and (4) laminating the sealed Microcups with a second conductor film. The resultant roll may then be cut to different sizes and formats⁽¹²⁻¹⁴⁾ for different applications.

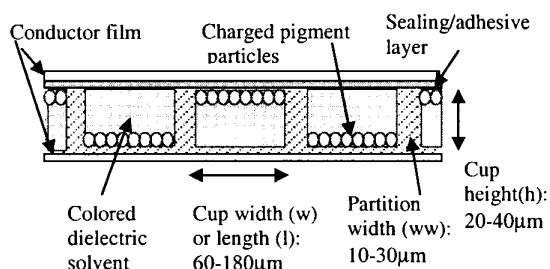


Figure 1 Schematic cross-section of a typical Microcup EPD. Each Microcup is isolated and seamlessly sealed.

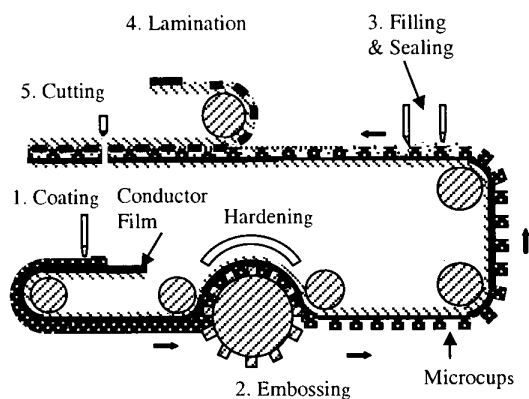


Figure 2 Schematic process flow of a typical SiPix roll-to-roll EPD manufacturing process

Surface profiles of two typical Microcup arrays are shown in Figure 3A and 3B. An optical photograph of the cross-section of a sealed square Microcup array (3A) having a dimension of $100\mu\text{m}$ (w and l) \times $30\mu\text{m}$ (h) \times $15\mu\text{m}$ (ww) and a sealing/adhesive layer of about $5\text{-}6\mu\text{m}$ is shown in Figure 3C. The typical total thickness of the sealing layer and the lamination adhesive is about $3\text{-}8\mu\text{m}$.

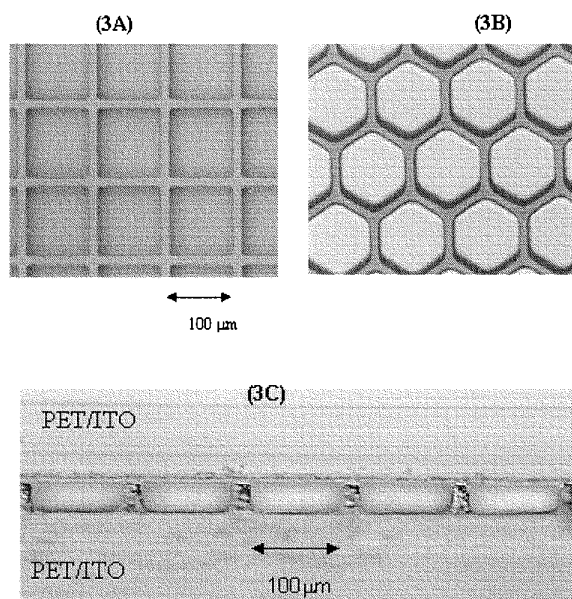


Figure 3A & 3B Surface profiles of two typical Microcup arrays as measured by a Wyko NT1000 Surface Profiler; **Figure 3C** Optical photography of cross-section of a sealed Microcup array 3A.

As it can be seen in Figure 3C, the electrophoretic fluid in each Microcup is surrounded by highly crosslinked partition walls ($10\text{-}30\mu\text{m}$ wide) and seamlessly sealed with a durable polymeric sealing layer ($2\text{-}8\mu\text{m}$ thick). As a result, the Microcup EPDs exhibit extraordinary mechanical durability and may be cut into different size and shape without the risk of leaking out the fluid. Color displays may be realized by overlaying a color filter onto the monochrome display or by selectively filling or printing R,G,B color fluids in predetermined Microcups with registration, followed by one of the SiPix sealing processes⁽¹²⁻¹⁴⁾ that will be described later.

PIGMENT MICROPARTICLES

The proprietary charged pigment microparticles are submicron in size with a narrow size distribution and are density-matched very closely to the dielectric solvent. Excellent stability has been observed even after centrifuged at 1000G for more than 30 minutes.

FILLING AND SEALING PROCESSES

The filling and sealing processes are the critical steps of the roll-to-roll manufacturing process. The traditional edge sealing and vacuum filling processes for assembling a LCD cell are not useful at all for the Microcup structure. Directly laminating a conductor film with or without a pre-coated adhesive onto the filled Microcups typically results in poor sealing with unacceptable defects such as de-wetting, delamination, trapped-in air pocket or void, and non-uniform image quality. To enable the roll-to-roll manufacturing of Microcup EPDs, two high speed, continuous filling and sealing processes have been developed successfully (Figure 4 and 5). High quality seamless sealing of the filled Microcups has been demonstrated at a speed of more than $30\text{ft}/\text{min}$ by both processes. Excellent barrier properties against solvent evaporation has been observed as evident by the negligible weight loss after prolonged baking of the sealed Microcups in an 80°C oven.

In the SiPix 1-pass filling and sealing process (Figure 4), a sealing composition is pre-emulsified in the electrophoretic fluid containing density-matched pigment microparticles and coated onto the Microcups (4A). The sealing composition is optimized to allow fast phase separation and creaming of the sealing layer to form a contiguous film with acceptable integrity on the top of the filled Microcups (4B). The phase separated sealing layer may then be hardened by methods such as solvent evaporation, thermal and radiation curing to enclose the fluid in the Microcups (Figure 4C).

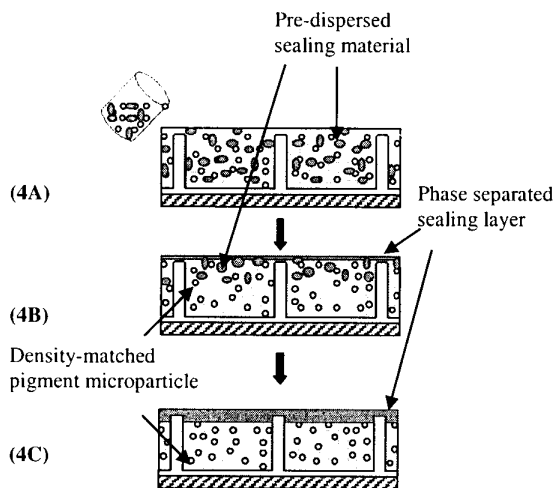


Figure 4 Schematic SiPix 1-pass sealing process
 (4A) Filling the electrophoretic fluid with a pre-emulsified sealing composition therein;
 (4B) Phase separation and floating of the lighter sealing composition;
 (4C) Hardening the sealing layer

Alternatively, the Microcups may be filled and sealed by the SiPix 2-pass process (Figure 5). The Microcups are partially filled by an electrophoretic fluid (5A), followed by overcoating the filled Microcups with a sealing layer (5B) and, drying and hardening the sealing layer (5C) by for examples, interfacial polymerization/crosslinking, moisture, radiation, and thermal curing, or their combinations.

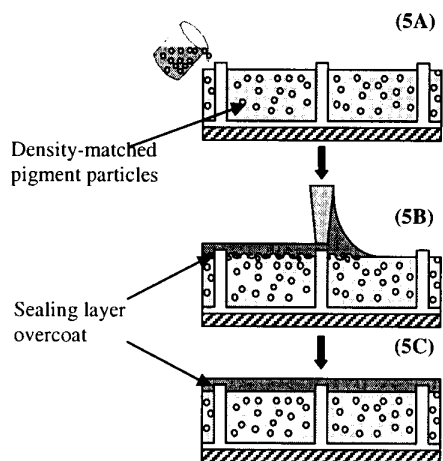


Figure 5 Schematic SiPix 2-pass sealing process
 (5A) Filling the Microcup
 (5B) Overcoating a light, incompatible sealing layer onto the partially filled microcup
 (5C) Phase separation and hardening of the sealing layer

To achieve an acceptable seamless sealing by either process, at least six critical parameters must be optimized: (1) the density difference between the sealing composition and the electrophoretic fluid, (2) the degree of incompatibility among the pigment microparticles, the dielectric solvent, and the sealing composition, (3) the surface tension and interfacial tension of all interfaces or surfaces involved, (4) the interaction between the sealing composition and the partition walls, (5) the rheology of both the sealing composition and the electrophoretic fluid, and (6) the integrity and physico-mechanical properties of the sealing layer during and after sealing. The 1-pass sealing process is very attractive because of its simplicity. However, the 2-pass process is very useful particularly when the sealing composition is at least partially compatible with the electrophoretic fluid. Roll-to-roll filling and sealing of displays other than EPDs have also been demonstrated by both SiPix processes⁽¹⁵⁾.

THE SIPIX MICROCUP EPDS

Rolls of flexible EPD panels as thin as 0.15mm and as light as 0.4gm/in² have been manufactured by the SiPix roll-to-roll processes. After the roll is cut to a desirable size and format, the polymeric layers covering both conductor electrodes may be removed easily by a proprietary stripper to facilitate the bonding to FPCs and driver IC connectors. A schematic structure of the SiPix Microcup EPD is shown in Figure 6.

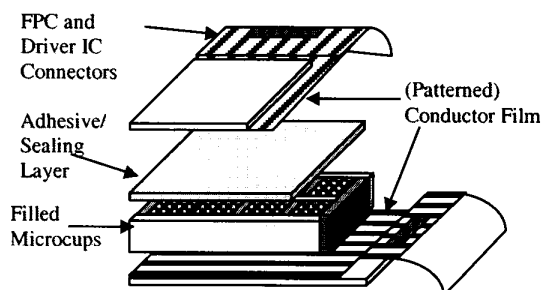


Figure 6 Schematic structure of a SiPix EPD

Bistable, reflective displays having a response time <100 msec, a contrast ratio (CR) ≥ 10 at $\pm 15V$ with an edge sharpness ≥ 300 dpi, a viewing angle of about 180° , and an extremely low degree of image graininess have been demonstrated. Negligible loss of contrast ratio was observed even at high humidity after the power was turned off for more than 24 hours. Power consumption is extremely low (in the μW range) partly because of the extraordinary image bistability and low operating current ($\leq 0.02\mu A/cm^2$ at 20V).

PASSIVE MATRIX MICROCUP EPDS

The characteristic response curves and waveform of a passive matrix Microcup EPD for e-sign or similar applications are shown in Figure 7. A threshold voltage (V_s) of $\geq 25V$ with a CR of ≥ 15 , and a t_{on} of $\leq 150msec$, a t_{off} $\leq 50msec$ at a driving voltage of $\pm 45V$ can be seen clearly in Figure 7A and 7B. No optical response was observed at adjacent pixel driven at a bias voltage of $\pm 15V$. By optimizing the compositions of the electrophoretic fluid, the Microcups, and the sealing/adhesive layers, high performance passive matrix Microcup EPDs having threshold voltages ranging from 5-50V have been obtained (Figure 8).

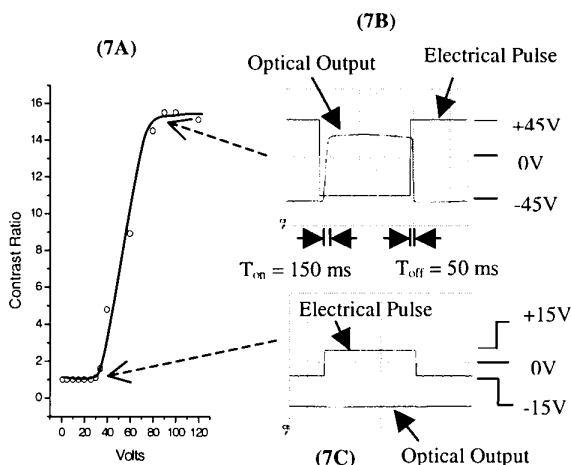


Figure 7 Characteristic curves of a passive matrix Microcup EPD

- (7A) CR vs. applied voltage curve showing a V_s of about 25V, a CR of about 15 with $t_{on} \leq 150ms$, and $t_{off} \leq 50ms$ at $\pm 45V$;
 (7B) Optical output and driving waveform at $\pm 45V$;
 (7C) Optical output and driving waveform at $\pm 15V$.

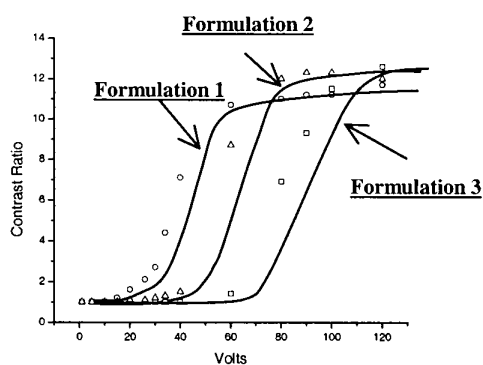


Figure 8 CR vs. applied voltage curves of three Microcup EPDs showing high CRs with threshold voltages ranging from 5-50volts.

Figure 9A shows an optical photograph of a segment Microcup EPD operating at $\pm 15V$ while the display was bended at about 120° angle. Figure 9B shows that the segment Microcup EPD has maintained its good performance even after the display was cut. The excellent format flexibility allows displays of different size and shape to be made from the same jumbo roll of EPD panel prepared by the continuous roll-to-roll manufacturing process.

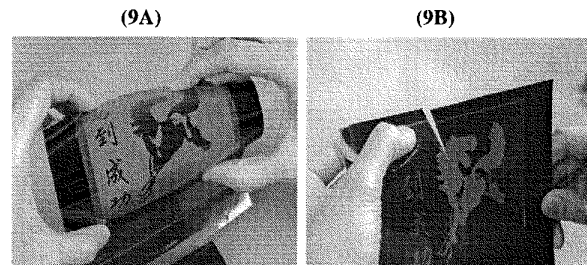


Figure 9 Photographs of a segment Microcup EPD switched at $\pm 15V$; (A) switched at 120° bend angle (B) switched well even after the display was cut.

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