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Microcup® Electronic Paper by Roll-to-Roll Manufacturing Processes

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ABSTRACT

Recently, a high-velocity roll-to-roll production method based on SiPix's innovative Microcup® and top-sealing technologies has been used to create rolls of electronic paper(1-8). There have been demonstrations of both LCDs and Microcup® electrophoretic displays (EPDs). This electronic paper is very thin, lightweight, format adaptable, and long-lasting. It has also been shown that both active and passive matrices may be used to create EPDs with a high switching rate and a broad operating temperature and threshold voltage range.

INTRODUCTION

Reflective displays that combine excellent performance, flexibility, and durability with cheap production cost have been a target of researchers for a long time. In recent years, there has been a resurgence of interest in electrophoretic displays, which use the electrophoresis of pigment particles and have been publicly published since 1969(9-13). Recent disclosures have shown several exciting developments, such as microencapsulated EPDs(14–16), In-Plane EPDs(17–19), Reverse Emulsion EPDs(20), and Total Internal Reflection(21). Although there have been several attempts to create an EPD, none have been commercially successful due to (1) the high cost associated with inefficient production techniques and materials and (2) the technological problems in constructing passive matrix EPDs(9,13, 22-24).

Roll-to-roll EPD production using SiPix Imaging's innovative Microcup® and top-sealing technologies(1-8) has just been made public knowledge. On a continuous plastic web, we have been able to produce ultra-thin, ultra-light, robust, and flexible EPDs at extremely high speed and cheap cost, with good format flexibility and many desired display capabilities. Microcup® EPDs with low-voltage driving, active and passive matrices, and both direct and inverse photodiodes have all been shown in practice.

The absence of intrinsic threshold characteristics in a PMEPD built using the standard column and row electrode matrix has long been seen as a significant technological barrier. While compromises in reaction time, operating voltage, brightness, picture uniformity, and display lifetime have been reported(24) for an electrophoretic fluid with certain threshold properties, these compromises are not ideal. SiPix, on the other hand, has successfully produced Microcup® PMEPDs with reliable threshold properties, including threshold voltages ranging from 550V throughout a broad working temperature range (2070oC)(13, 22). There does not seem to be any compromise in colloidal or storage stability.

MICROCUPS® ROLL-TO-ROLL MANUFACTURING PROCESSES

Electrophoretic fluids, consisting of sub-micron, charged pigment (TiO2) microparticles distributed in density-matched color solvents, are contained and smoothly sealed in the Microcups, as shown in the schematic representation of a typical Microcup EPD in Figure 1. Microcups® for EPDs typically have dimensions in the range of 60–180 um (w or l) x 12–40 um (h) x 5–25 um (ww), however these numbers might change depending on the application. Microcups with a diameter of just 13 um were utilized in LCD displays.

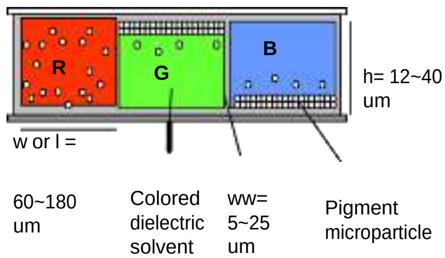

Figure 1 Schematic cross-section of a color Microcup® EPD. Each microcup is isolated and seamlessly top-sealed.

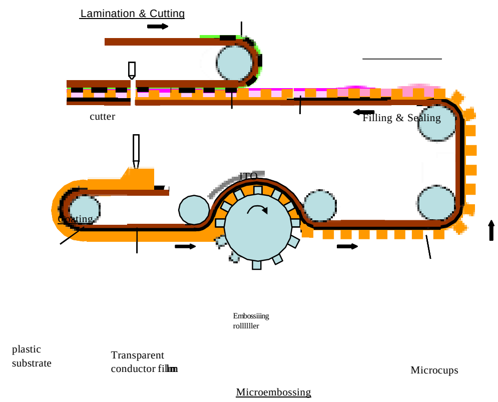

Figure 2 Schematic process flow of the SiPix roll-to-roll electronic paper manufacturing process

Figure 2 depicts a simplified process flow for producing SiPix on a roll-to-roll basis. Microcup® EPD rolls have been prepared by, for instance, (1) coating an ITO/PET film with a UV curable composition; (2) embossing and hardening the UV composition; (3) filling the Microcups with electrophoretic fluid; (4) top-sealing the filled Microcups® seamlessly; and (5) laminating the top-sealed Microcups® with a release liner or a second conductor film. Figure 3 depicts the cross-section of a filled and sealed sample, as well as the usual construction of a Microcup. Color EPDs may be achieved with the addition of a color filter to the monochrome display, or through the registration-assisted filling or printing of R, G, B color fluids in specified Microcups.

(3A)

(3B)

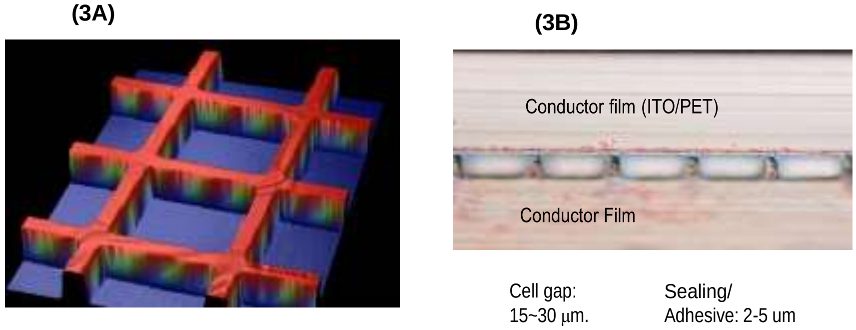

Figure 3 A typical Microcup® structure (3A) and the cross-section of filled and sealed sample (3B).

SIPIX'S TOP-SEALING AND CONVERTING PROCESSES

Roll-to-roll production relies heavily on the filling and sealing operations. The Microcup® shape has no use for the standard LCD cell assembly methods of edge sealing and vacuum filling. Poor sealing with undesirable flaws such as de-wetting, de-lamination, trapped-in air pocket or void, and non-uniform picture quality is usual when laminating a conductor film directly onto the filled Microcups, with or without a pre-coated adhesive. Two successful continuous filling and top-sealing procedures allow Microcup® EPDs to be manufactured on a roll-to-roll basis. Seamless sealing of full Microcups at speeds more than 30 feet per minute have been shown using both methods.

Coating the Microcups with an electrophoretic solution containing pigment microparticles with a density that is a perfect match is the first step in the SiPix 1-pass filling and sealing procedures. To ensure that the sealed Microcups maintain their structural integrity, the sealing composition is tailored for rapid phase separation and creaming of the sealing layer. After the fluid is contained in the Microcups, the phase separated sealing layer may be toughened using processes including solvent evaporation, heating, or radiation.

The SiPix 2-pass top-sealing procedure may also be used to fill and seal the Microcups. An electrophoretic fluid is injected into the Microcups to a partial depth, then the Microcups are coated with a sealing layer, and finally the sealing layer is dried and hardened by interfacial polymerization/crosslinking, moisture, radiation, thermal curing, or any combination thereof. Both top-sealing techniques have shown capable of producing a watertight seal.

According to the TGA heating rate technique, the activation energy of solvent penetration through the top-sealing layer is around 26 Kcal/mol, and the commencement of weight loss temperature is approximately 230oC(4, 8). Since the dielectric solvent may be kept in good condition before the following conversion procedures, the as-sealed Microcups® have a long process green time due to their high Tonset and high barrier activation energy. The top sealing layer's superior barrier qualities also enable the use of a solvent with a low boiling point, whose viscosity is reasonably insensitive to variations in temperature within the relevant range. Microcup® EPD optical response is shown to be very stable between 0 and 70 degrees Celsius. With a thermal adjustment system, the temperature range might be pushed all the way down to -20oC.

Rolls of pre-laminated PMEPD, sandwiched between row and column electrodes, and rolls of ready-to-laminate EPD, sandwiched between a release liner and a patterned or non-patterned electrode film, have both been produced using the SiPix roll-to-roll process(2),(4),26 to produce Microcup EPD films as thin as 0.12 mm and as light as 0.4 gm/in2. Both kinds of EPD rolls may be easily trimmed to size, and then stripped to reveal the electrodes. The as-sealed Microcup® film is laminated onto a commercially available a-Si TFT back plane to create an active matrix display (AMEPD). At a driving voltage of roughly +10 volts, the AMEPD has shown a contrast ratio of >8, a frame rate of 0.4 sec, and an image bistability of >24 hours.

PASSIVE MATRIX MICROCUP® EPD

The SiPix roll-to-roll method using column and row patterned ITO/PET films has also been used to create high performance Microcup® PMEPDs at high throughput. It has been shown that passive matrix Microcup EPDs with threshold voltages in the 5-50V range may be achieved by adjusting the compositions of the electrophoretic fluid, the Microcups, and the sealing/adhesive layers(1). Microcup® PMEPDs' typical electro-optical response curve is seen in Figure 4. In order to achieve such high performance with just row and column ITO electrodes on a plastic substrate, the SiPix proprietary pigment-containing microparticles, as well as the unique Microcup® structure and top-sealing process, appear to provide extremely wide formulation and process windows for the optimization of all of the aforementioned compositions. Recently, a prototype 110 dpi, 160x160 lines PMEPD was exhibited utilizing standard row and column STN drivers at around 40-60 V, achieving a switching speed of 20-30 msec/line (or a frame rate of about 3-5 sec) with a contrast ratio of about 10. Using more drivers or a greater driving voltage may increase the frame rate. Pulse amplitude, pulse width, and pulse count modulation mechanisms, or their combinations(4, 8), may be used to provide gray scale in the Microcup® PMEPD without sacrificing pixel resolution. Figure 5 demonstrates that an 8-level Microcup® PMEPD exhibits bistability in grayscale images for more than 120 hours.

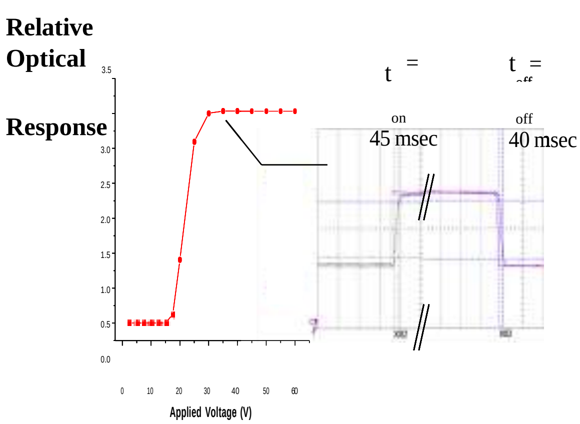

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Figure 4 Electro-optical response of a typical Microcup® PMEPD.

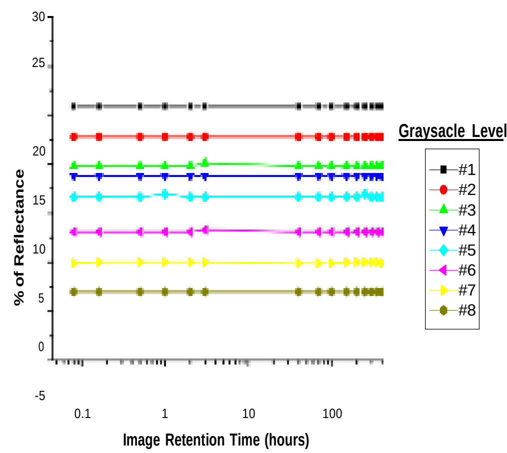

Figure 5 Grayscale stability of a typical Microcup® PMEPD at the power-off state.

MICROCUP® EPD DEVICE DRIVING SCHEMES(27)

Microcup® EPDs can be modeled as a simplified network, with the electrophoretic fluid representing the bottom Rd//Cd circuit and the insulator layers, such as Microcup®, sealing and adhesive layers, representing the top Ri//Ci circuit, in accordance with the electrical properties of the Microcup® materials and structures. When using a standard DC driving waveform, it's best if Rd is bigger than Ri. In order to provide a bigger bias voltage to the electrophoretic fluid, it is optimal for Ci to be larger than Cd during the transient state. Selecting an electrophoretic fluid with a threshold effect and driving voltages that minimize cross-talk voltage in a passive matrix EPD. A 3x3 dot matrix with 3 column electrodes on top (the viewing electrodes) is used for clarity.

lateral) and three rows of electrodes (bottom) to demonstrate the driving mechanism. Setting all column electrodes to 30V and all row electrodes to 0V returns the 3x3 passive matrix EPD to its initial blue state. Throughout the virtual driving experience, an electrophoretic fluid was employed, which consisted of positively charged, white pigment microparticles distributed in a blue solvent. It is believed that 12 V is the threshold effect.

The waveform used to produce a particular pattern while driving the three pixels (P1, P2, and P3) in the first row is seen in Figure 6. Here, we're making P1 and P3 into white while keeping P2 in blue. The voltage of an addressed row is set to 30V, whereas the voltage of an unaddressed row is set to 10V. When pixels P1 and P3 are set to white, the associated column electrode is grounded at 0V. When pixel P2 is maintained in its blue condition, the associated column electrode is given 20V. White-state pixels are given a bias voltage of 30V thanks to the aforementioned driving voltage setup. Pixels that should remain blue are given a +10V bias. In this voltage setup, the cross-talk bias voltage may be either +10V or -10V. A voltage threshold of 12V is required to get rid of the cross-talk effect. There have also been proposals for dual mode driving strategies for full color displays(27).

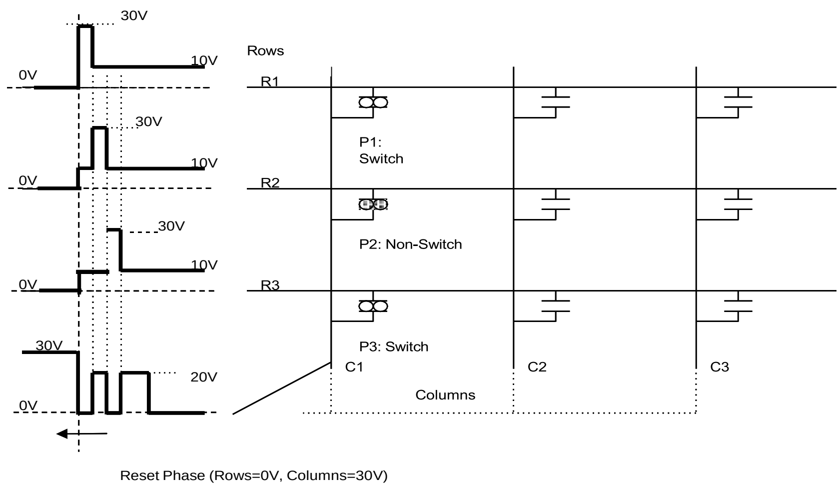

Figure 6 Driving waveforms of a Passive Matrix Micropcup® EPD

APPLICATIONS OF MICROCUP® ELECTRONIC PAPER

Commonly cited benefits of EPDs include a wide viewing angle, bistability, low power consumption, and the absence of a polarizer. SiPix Microcup® EPDs provide a unique color solution without the need for a color filter; they are also more flexible, durable, environmentally stable, format free, thin and light, inexpensive to manufacture, and productive in terms of throughput.

Flexible direct drive or active matrix back-planes are suitable for laminating SiPix Microcup® EPDs. SiPix has also shown it can make a passive matrix display that can bend in any direction. Non-active matrices Driver chips for the flexible film, or "Chip-on-Flex," will be affixed to its edges. The screen may be bent or shaped by software into various flat or curved forms. Furthermore, the

The display's flexibility and durability against scratches and impacts are a result of the SiPix Microcup® construction.

The SiPix EPD materials were developed with extreme durability in mind. There is no need for additional environmental barriers. In particular, the materials are impervious to the effects of moisture. The screen will still function even if submerged.

The smart card is an early implementation of SiPix Microcup® EPD technology. To bring the first EPD-display smart card to market, SiPix has partnered with SmartDisplayer® (www.smartdisplayer.com) in Taiwan. The low power bi-stability, flexibility, and durability of the SiPix Microcup® EPD are essential in the smart card application. The card may include the ultra-thin, flexible SiPix display.

The SiPix Microcup® EPD is ideal for use in electronic price tags, point-of-purchase signage, and other electronic displays. High contrast paper-like images with a broad viewing angle and low power consumption are essential features for digital signage. Higher resolution signs, ads, and message boards are just some of the potential new uses for electronic signage as technology advances and passive matrix displays grow in size and capacity. The electronic sign's information content will have more leeway with passive matrix.

Because of their adaptability and resilience, these materials provide for safer alternatives to glass in children's items. Toys, games, and educational tools are all examples of kid-friendly software. These applications often use smaller passive matrix monochrome displays or segment types with lesser resolution.

The SiPix Microcup® EPD will ultimately replace LCDs in a wide variety of applications. Devices like digital watches, calculators, phones, and clocks fall under this category. The thin, flexible, robust, and bi-stable properties will allow for innovative new form factors and increase the wearability of specific items.

Many novel idea applications have been presented during the development and introduction of electronic paper. Ideas include high-resolution digital newspapers and printable, rewritable electronic paper. SiPix Microcup® EPD technology will eventually allow for all ideas and potential applications involving electronic paper, including photoimageable Microcup® electronic paper with a photoconductive back plane.

Any new display technology's commercial adoption and penetration will rely on price in addition to its technological qualities. SiPix's proprietary roll-to-roll manufacturing technique was created with the goal of producing high quality products at affordable costs. Additional electronic paper applications will be developed, and current businesses will grow, thanks to the SiPix manufacturing cost advantage. It will also let SiPix compete more effectively in a wider range of sectors now dominated by LCD.

CONCLUSIONS

The SiPix roll-to-roll manufacturing technique has been used to manufacture high-performance Microcup® electronic paper or displays at cheap cost and with a high throughput. The top-sealing methods and distinctive Microcup® structure provide superior physicomechanical qualities and accommodating formats. They also make it possible to adjust the display's performance by tailoring the compositions of the electrophoretic fluid, the Microcups®, and the top-sealing and adhesive layers separately.

Since proving the viability of the roll-to-roll Microcup® technologies in the early 2000s, SiPix has assembled a world-class team of over 90 scientists & engineers in the Silicon Valley for research & development and pilot production, and another team of about 20 in Taiwan for module integration and business partnership. Since late 2002, a prototype production plant with a capacity of over 10 million ft2/yr has been constructed and put through its paces in Fremont, California. There hasn't been a roll-to-roll manufacturing process like this for electronic paper or screens before.

The core of SiPix's business strategy is to provide electronic paper/film through strategic partnerships with other firms that manufacture modules used in electronic devices. SiPix is planning to release its direct drive products in late 2003 and the flexible passive matrix electronic paper in the summer of 2004 with the help of funding from investors and partners such as Goldman Sachs, Bearing Private, Worldview, and Pacific Technology Investment. Meanwhile, SiPix is actively collaborating with partners to advance active matrix and true color (no color filter) display technology.

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