An Investigation of Characterizing Screen Printing Conditions for Producing Electroluminescent Halftone Display

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Keywords: screen printing, electroluminescent display, halftone, characterizing, conductive inks

Abstract

Electroluminescent (EL) displays printed with graphic printing device serves the new demand on lighting and attention grasping marketing. With the developments in materials and electronics technology, printing with electroluminescent inks has been explored by the traditional graphic printing industry in combining graphics and functional materials for producing effective marketing tools. The ability of printing on flexible substrates opens up more opportunities for using electroluminescent materials in building flexible lamps, signage, active packaging, and much more. Electroluminescent lighting is used for backlighting in many display applications. For displaying color images, a transparent image is lit up by placing EL light on the back of the transparent color image. This research investigated screen printing process for producing halftone monochrome EL displays. Printing conditions and qualities, such as mesh counts, ink film thickness, and luminance level of EL lighting were discussed. Halftone displays with different tone values were produced with different printing conditions. The results showed that it is possible to produce monochrome halftone EL displays by patterning the phosphor layer. The luminance of the display was found to be highly related to the characteristics of dielectric layer and electrodes.

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Introduction

Printed electronics is projected to grow to a $300 billion dollar industry in the next decade. The driving force of using traditional printing technologies in producing functional devices, such as transistors, sensors, photovoltaics, lightings, and displays, is that the cost of production is much lower than traditional silicon processes. Printed electronics can be embedded with traditional graphic products for marketing purposes. Such products include smart packaging, point-of-purchase display, etc.

There were many developments in the area of material formulation and modification in the past few years. Many functional materials for lighting and display are now commercially available. However, there are disconnections between material developers and end users. The lack of creative ideas limits the use of the technology of printed electronics. Materials developers have limited understanding of commercial graphic printing. The materials are mostly tested on the lab scale devices rather than on commercially available large-scale presses. There are needs from materials developers to test their products on large-scale press for mass production. Printing providers have limited understanding of how functional materials can be printed, and the requirements of changing printing conditions to accommodate the special needs of such materials. Functional inks are different from conventional graphic inks in many ways. Functional inks require powerful drying and precise control of ink rheology and ink deposition. Printing conditions, such as printing speed, printing pressure, drying temperature, etc. have to be modified for printing functional inks. Consumer product developers have limited understanding of how to design a product to integrate the technology, especially the specifications for functional materials, for example, how thick the line could be, how much space should one material apart from another material, etc.

Electroluminescent (EL) display is the phenomenon of light emission due to a strong electric field (Wikipedia, electroluminescent). A typical EL display consists of solid-state thin film phosphor and insulator stack deposited on a glass substrate. Electroluminescent lighting requires low power consumption compared to other competing lighting technologies, such as neon or fluorescent lamps.

Electroluminescent displays are usually monochrome. To display a monochrome halftone, the image has to be converted to pixels. When the pixels are turned either on or off, a gray scale image could be displayed. For flat panel display, a controller could apply certain type of algorithms to manipulate the video data stream to provide some levels of gray scale. However, frame-based dithering writes only a portion of the frames so that the dimmed pixels are not written as often as bright pixels. This often causes objectionable video artifacts such as shimming, flicker, etc. (Planar, 2008) Other attempt of using electroluminescent cell to produce a halftone picture is using the light amplifier. Similar to the controller, current flow locally according to the intensity of the incident illumination, and the current pattern is transformed into an amplified image by the electroluminescent phosphor (Peaker, 1970).

The objectives of this research were to understand how printing parameters affect the performance of an EL display and the quality of displaying a halftone image with discrete phosphor units. The quality of EL solid and halftone displays was measured by the luminance level of the light that the device emitted. Surface roughness, ink film thickness, and sheet resistance of conducting materials were examined as well.

Experiments

Two sets of mesh were used for producing electroluminescent displays. One set of mesh was 305 tpi polyester mesh. Another set of mesh was 156 tpi polyester mesh. The meshes were stretched to the appropriate tension by the mesh manufacturer. The emulsion applied was RyoCap 30 microns capillary film. Silver, phosphor, dielectric inks, and sputtered ITO films were provided by Gwent Group.

The electroluminescent display was printed on ITO sputtered polyester film with the following building sequence shown in **Figure 1**. The first layer on the ITO sputtered polyester film was phosphor. Then two layers of dielectric were built on top of the phosphor. While building the two layers of dielectric, the second layer was printed with two different processes. One process was to print the first dielectric layer and dried with a conveyor dryer. The second layer of dielectric layer was printed on the dried dielectric ink. This process was recorded as wet-over-dry process. Another process was to print the second dielectric layer on top of the first dielectric layer without drying it. This process was recorded as wet-over-wet process. Silver ink was printed as rear electrode. There was no protective encapsulant printed for this study.

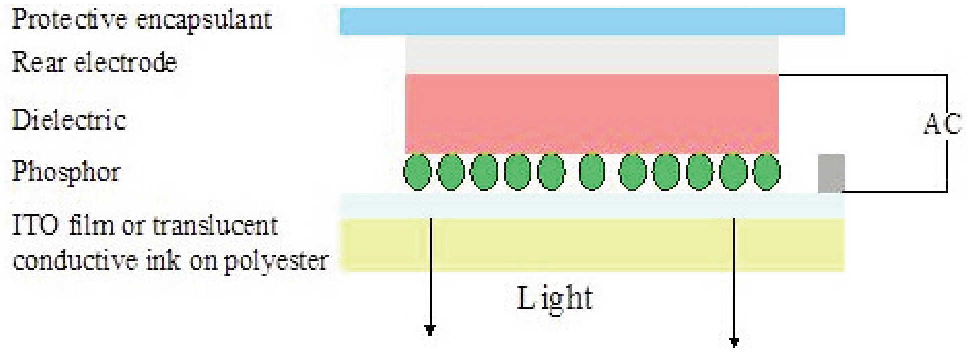

***Figure 1:** Electroluminescent display with sputtered ITO as front electrode (DuPont, 2006)*

As for common electroluminescent display, the phosphor layer is a large solid area. The device is usually used as lighting or as backlighting to illuminate the transparent image in front of it. In this research, the phosphor layer was produced with solid and halftone patterns. The image used for this study was shown in **Figure 2**.

The EL inks for the display were printed on an ATMA flatbed screen printing press. A convey dryer was used for dry the surface of the ink film between layers (except the case of printing two layers of dielectric ink). The assembled displays were placed in a lab scale oven for final curing.

The printing conditions were kept the same for different screen meshes. The snap distance was set at 1mm. The squeegee speed was set as 220mm/min. The squeegee pressure was set as 30bars.

Figure 2: *The image used for this study. The image was also patterned to 25%, 50%, and 75% dot percentages.*

The luminescent levels of the printed displays were measured with an x-rite EyeOne device. The surface roughness and sheet resistance of conductive layer were measured as well.

Results and Discussions

Thickness of dielectric layer

The dielectric layer in an EL display acts as insulator. The thickness of the dielectric layer is an important characteristic to the effective display. Thin dielectric film often encounters pinhole defects. One of the advantages of using screen printing to apply dielectric layer for EL display is that screen printing could deliver thick ink film. Thick dielectric layer boosts the dielectric strength and resistance to electric breakdown, eliminates the problem of pinhole defects, reduces the susceptibility of contamination during processing (Shionoya 2007). To achieve a thick dielectric film, two passes are usually required. Two ways of preparing the dielectric layer was conducted, which were referred as wet-on-wet printing and wet-on-dry printing as stated in the previous session.

The thickness of the dielectric layer was measured with a laser displacement system. The results were shown in the following table **(Table 1)**.

	Wet over wet	Wet over dry
156 threads/inch	12.2μm	18.5μm
305 threads/inch	9.2μm	13.8μm

Table 1: *Dielectric ink film thickness of two passes that were printed at different conditions.*

While printed at different conditions, different ink film thicknesses were achieved. A thicker ink film could be obtained when the second layer of dielectric ink printed on top of the previously dried dielectric ink film. This could be explained as that the ink transfer of second layer was more efficient when printed on a dried surface than on a wet surface.

Surface roughness

Surface characteristics are important to the performance of certain functional ink. A rough surface usually causes pinholes and other defects. This is particularly important for insulator as pinholes could cause shorting.

A TR200 Roughness Tester was used to determine the unevenness of the ink film. The unevenness of the ink film was described as roughness average Ra. Ra is the arithmetic average of the absolute values of the roughness profile ordinates (Wikipedia, surface roughness). The measurements were done on the following surfaces: ITO sputtered sheet, silver ink printed directly over the ITO surface, the dielectric ink printed at different printing conditions, the silver ink printed over the dielectric ink surfaces. The results were shown in **Table 2**.

Surface/Ra	ITO	Silver over ITO	Dielectric Wet over Wet	Dielectric Wet over Dry	Silver over Dielectric Wet over Wet	Silver over Dielectric Wet over Dry
156 threads/inch	0.106μm	2.097μm	0.683μm	0.740μm	1.191μm	1.874μm
305 threads/inch		1.681μm	0.463μm	0.544μm	0.809μm	1.112μm

Table 2: *Roughness data of different surfaces described as Ra*

Silver ink appeared to have different roughness values on different surfaces. When the silver ink was printed directly over the sputtered ITO surface, it appeared to have higher roughness than printed over the dielectric surface. This may be related to the wetting property of silver ink over ITO film. The silver ink showed poor adhesion to the ITO film could also be related to the wettability of ITO film.

Although the thickness of two layers of dielectric ink printed wet over wet resulted thinner ink film than the one printed by wet over dry process, the surface roughness of such dielectric ink film appeared to be lower. This may be explained as that two layers of wet dielectric ink could level better than a single layer of wet dielectric ink.

Sheet resistance

Sheet resistance is a measurement of resistance of thin film that is nominally uniform in thickness. A Jandel HM-21Four-Point Probe Test Unit was used to measure the sheet resistance. Silver ink was printed over dielectric to work as the back electrode. In the meanwhile, a silver bus bar was printed directly on sputtered ITO film to charge the transparent conductor ITO. The ITO surface became the front electrode. The conductivity of the electrodes impacts the efficiency of the display. Sheet resistance measurements were done on the sputtered ITO surface, the silver ink printed over ITO film, and the silver ink printed over dielectric ink surface. **Table 3** presented the results.

Surface/Sheet Resistance (Ω/□)	ITO	Silver over ITO	Silver over Wet over Wet Printed Dielectric	Silver over Wet over Dry Printed Dielectric
156 threads/inch	65.5	2.8	1.1	1.5
305 threads/inch		8.5	2.1	2.9

Table 3: *Sheet resistance data for conductors over different surfaces.*

Sheet resistance of silver ink showed lower values when the ink was printed over the dielectric ink film. This corresponded well to the results obtained in the roughness test. Silver ink film appeared to higher roughness over ITO film than over the dielectric ink film. This may further prove that the dielectric ink film had better wetting property than the ITO film for this type of silver ink.

Roughness data of two layers of dielectric ink film printed differently (wet over wet and wet over dry processes) corresponded well to the sheet resistance of silver inks on top. Sheet resistance of the silver ink was higher when the ink was printed on the wet over dry stacked dielectric ink film. The roughness of the dielectric ink film may contribute to the sheet resistance of silver ink.

Overall, the silver ink printed with 156 threads/inch mesh had lower sheet resistance than the one printed with 305 threads/inch mesh. The thicker silver ink film had positive impact to lower the sheet resistance.

Halftone Images

Typical EL used as back lighting consists a phosphor layer with completely no pattern. In this study, the phosphor was patterned as a halftone image for display. Total four tone levels were tested, 100%, 75%, 50%, and 25%. The halftone images were printed with 156 threads/inch and 305 threads/inch screens at the same printing conditions described in the previous sessions. The luminescent levels were measured with an EyeOne device. The lightness level was recorded to compare the luminescent level of each display.

The following images showed the assembled displays at different dot percentages printed at same condition (**Figure 3** and **4**).

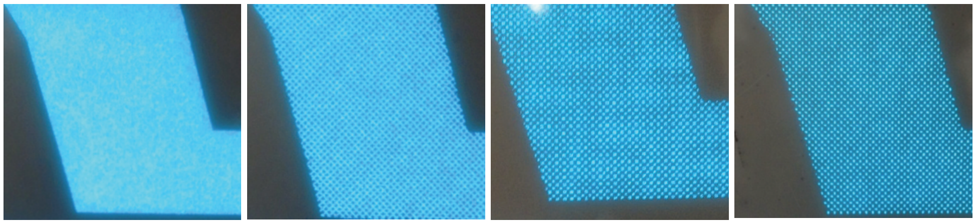

Figure 3: *Halftone displays printed with 305 threads/inch mesh.*
From left to right: 100%, 75%, 50%, 25%.

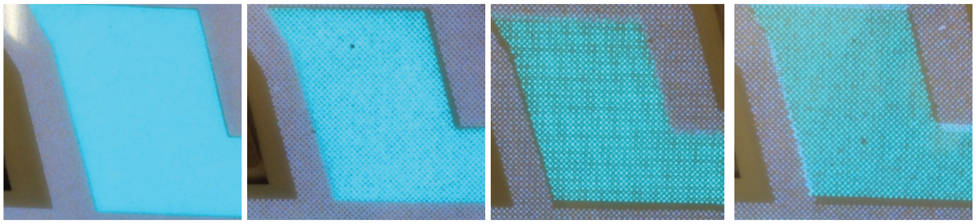

Figure 4: *Halftone displays printed with 156 threads/inch mesh.*
From left to right: 100%, 75%, 50%, 25%.

Based on visual assessments, the displays printed with 305 threads/inch mesh resulted good resolution. However, the solid display printed with 305 threads/inch mesh appeared to be less uniform than the one printed with 156 threads/inch mesh. This was due to the thinner phosphor ink film delivered by the finer mesh. **Figure 5** showed the phosphors printed with different mesh counts obtained by ImageXpert system.

It was clear that the phosphor printed with 305 threads/inch showed some uncovered areas, which contributed to the unevenness of the solid display.

The lightness reading captured by the EyeOne was recorded in **Table 4** and **5**.

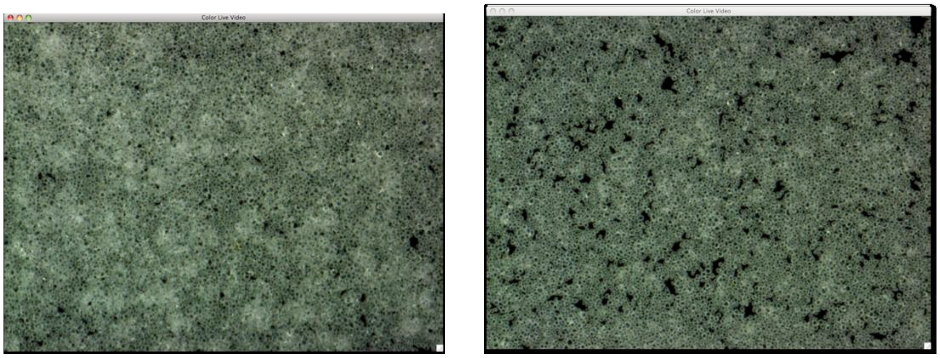

Figure 5: *Phosphors printed with different screen meshes of solid area. Left: printed with 156 threads/inch; right: printed with 305 threads/inch.*

Halftone (%)	100%	75%	50%	25%
156 threads/inch	120.86	109.25	78.34	60.24
305 threads/inch	125.62	112.57	93.48	71.62

Table 4: *Lightness values of halftone displays printed with two layers of dielectric inks wet over wet.*

Halftone (%)	100%	75%	50%	25%
156 threads/inch	111.46	100.26	69.18	54.32
305 threads/inch	111.44	92.46	71.42	56

Table 5: *Lightness values of halftone displays printed with two layers of dielectric inks wet over dry.*

The displays assembled with two layers of dielectric inks printed wet over wet had slightly lower luminescence level. As for ink film thickness, two layers of dielectric inks printed wet over wet was slightly thinner than the ones printed as wet over dry. The thickness of the dielectric layer could play an important role of affecting the electric field that applied over the phosphor. The could also explain why the displays printed with 305 threads/inch mesh had slightly higher luminescent level than the ones printed with 156 threads/inch due the thickness difference of dielectric ink films.

Problems Encountered

Halftone displays were printed with different mesh counts on the sputtered ITO films. The biggest problem observed was the adhesion of printed ink film to the ITO surface. This happened not only to the silver ink but also to the phosphor ink. However, the dielectric ink appeared to have good adhesion to the ITO surface. **Figure 6** showed the poor adhesion of silver ink and phosphor ink on the ITO surface. The phosphor with poor adhesion to ITO surface was not able to light up.

Figure 6: *Poor adhesion appeared between phosphor ink and ITO surface.*

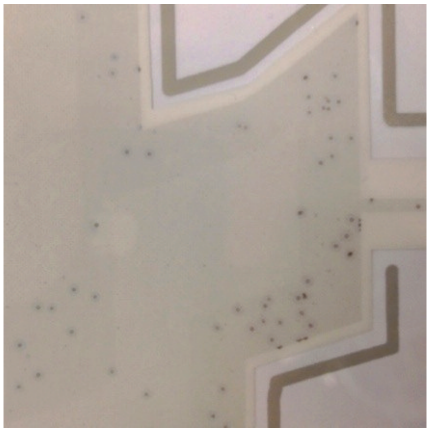

Figure 7: *Pinholes on dielectric layers caused shorting.*
The device was printed with 305 threads/inch screen.

Another problem encountered was pinholes as defects produced while printing dielectric ink. The dielectric ink acted as the insulator. Any pinhole could cause shorting while the device is powered on. **Figure 7** showed the defects of dielectric ink layer caused shortings. This appeared mostly on the displays that were printed with 305 threads/inch screens.

Conclusions

Electroluminescent halftone monochrome displays were built by screen printing process. Screens with different mesh counts were used. The quality of the display in terms of luminescence level was affected by print quality of each functional layer.

It was found that the dielectric layer played important role to display quality. In this study, dielectric layers were printed with two different processes. One process printed the two dielectric inks that had wet ink printed on top of the wet ink. Another process printed the two dielectric inks that had wet ink printed on top of the dried ink. These processes produced different ink film thickness and surface roughness. These differences also affected the characteristics of the layer printed on top of it, which was the silver back electrode.

The sheet resistance of silver ink printed on top of the dielectric layer was affected by the surface roughness of the dielectric layer. The silver ink printed on the rougher dielectric layer delivered higher sheet resistance. The stacked dielectric layer printed with wet over dry process produced thicker ink film. The thickness of the dielectric layer was found to correlate with the luminescence level. The device had thicker dielectric layer had slightly lower luminescence level.

Monochrome halftone EL images were produced by patterning the phosphor layer. The different luminescence levels were achieved by printing the phosphor as a halftone image. The images printed with finer mesh (305tpi) showed better resolution. However, the dielectric layer printed with finer mesh appeared to have more pinholes that causing shorting when the device was powered on.

Different mesh counts could deliver different ink film thicknesses. The phosphor ink printed with two different meshes appeared to have different display quality. The phosphor layer printed with finer mesh had more voids. Such phosphor layer shown uneven display when the device was powered on. However, the display with thinner phosphor had higher luminescence level.

Poor adhesion between phosphor and ITO film, the silver ink and ITO film were observed. Some printed displays with low adhesion between functional materials to ITO film were not able to light up.

ITO film is typically fragile and more rigid. For building a more flexible EL display, other transparent conductors are worth investigating.

Acknowledgements

This project was supported by Gwent Group that provided the ITO sheets and electroluminescent inks. The printing was done on an ATMA flatbed screen printing press donated by Apple, Inc. Some images were taken with an ImageXpert system.

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