Solution Processable P-OLED (Polymer Organic Light Emitting Diode) Display Technology.

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1. Abstract

We report the development frontiers that are dictating the speed of adoption of polymer organic light emitting diode (P-OLED) technology in market applications. Our presentation includes both the developments taking place in materials and the rapid advances in the manufacturing processes used for solution processable P-OLEDs. On the manufacturing side, the latest progress in ink jet printing process is discussed. On the materials side, we look at both fluorescent and phosphorescent material performance including the CDT development roadmap.

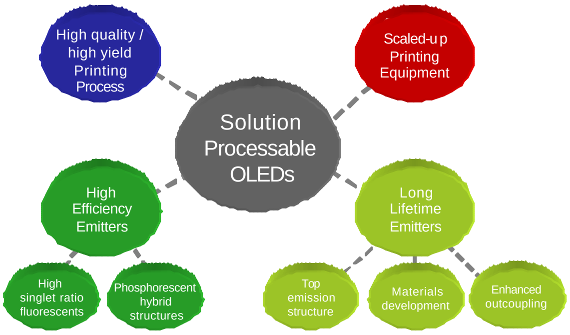
2. Introduction

P-OLED technology provides a new alternative to TFT-LCD for many display applications, and is particularly attractive in terms of its brightness, wide viewing angle, fast response time and low power consumption. Since 2002, several companies such as Philips, OSRAM, DuPont, Seiko-Epson, TMD (Toshiba-Matsushita Display), Casio, Samsung Electronics, Delta and CDT have been developing AM-PLED and PM-PLED technology and have already demonstrated P-OLED displays. In recent years, P-OLED technology has made tremendous progress in terms of display performance (including life time, efficiency and available color gamut) and maturity of manufacturing processes and equipment. [1] [2]

OLED technology is now emerging as a leading candidate among the many technologies under development for next generation flat panel displays. The forecast for market size of OLED display presented by Display Research is expected to reach \$3.85 billion in 2007 and \$5.3 billion in 2008[3], which demonstrate the need for volume production. MP3 players, mobile phones and portable DVD applications will drive growth in the OLED market through 2006. OLED manufacturing costs will be competitive with a-Si TFT LCD in small/medium display market if manufacturing technology optimize on TACT, material utilization and equipment utilization.

In order to get into this market successfully, P-OLED display technology must meet the following display makers' requirements: (1) P-OLED Display Performance in terms of lifetime, efficiency, and color coordinates.(2) Low Cost Manufacturing Technology such as "Solution Processable P-OLED Display Technology".

Fig1. Development across all Technology Fields

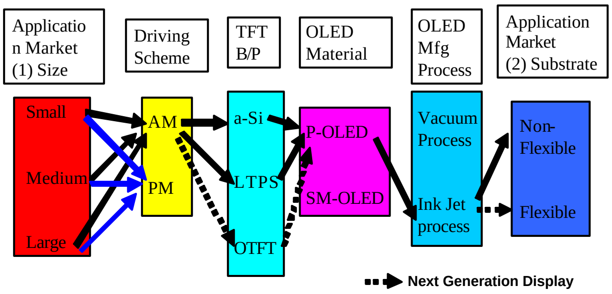


In this paper, we give an update on developments by CDT and its licensees taking place in materials and the rapid advances in the manufacturing processes used for solution processable P-OLEDs shown in Fig.1

3. Solution Processable Ink Jet Technology

In order to choose the best method of OLED volume production we need to consider the following factors: (1) Application Market (2) Driving Scheme (3) TFT Back Plane (4) OLED Material (5) OLED Process and (6) Substrate shown in Fig.2

Fig.2 The Way of P-OLED Manufacturing



Low Cost !!!, Scaled-Up to Gen.7/8, Possibility of Flexible Display

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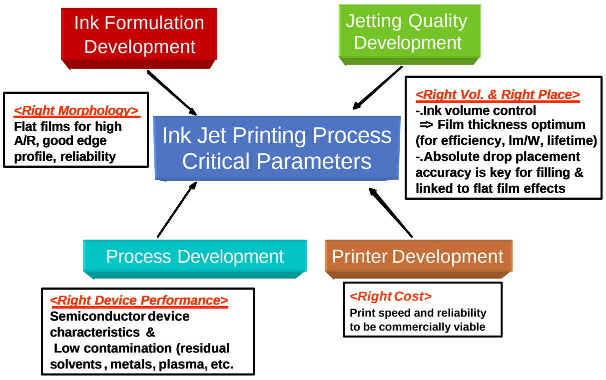
One characteristic that is very promising from a manufacturing perspective is that P-OLED materials are "Solution-Processable" unlike the vacuum-deposited material used to fabricate small molecule-OLED (SM-OLED) displays. The solution processable ink jet printing (IJP) technology of P-OLED has several benefits for manufacturing over SM-OLED including scalability up to Gen.7/8 and the possibility to make high resolution display. However, there are still challenges to be overcome in terms of jetting reliability.

The critical key parameters for "Solution Processable Ink Jet Technology" summarised in Fig.3 are:
(1) Ink Formulation Development
(2) Jetting Quality Development
(3) Printer Development with High Performance
(4) Process Development

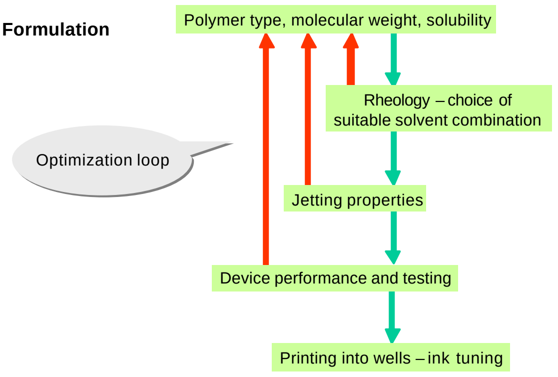
Fig. 3 Ink Jet Printing Process Critical Parameter.



3.1. Ink Formulation Development

One of the main challenges for reliable jetting is to optimize the ink formulation of the LEP and hole transport layer inks. These inks are carefully formulated solutions of the active polymer materials in one or more carrier solvents. The polymer inks must be formulated so that they jet very well, form flat uniform films, are stable in solution so that they do not block the very small printhead nozzles, and demonstrate as good as(or preferably better than) device performance as spin coated devices.
The typical optimization procedure of ink formulation development is showed in Fig.4.

Fig 4. Optimum Ink Formulation Procedure.



3-2. Jetting Quality Development

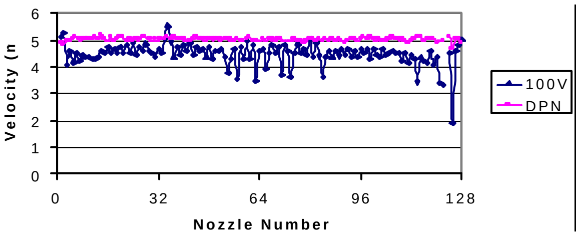
The jetting quality, defined by the drop volume, drop velocity, and drop placement accuracy directly affects display quality and in particular the image uniformity of the display. These parameters depend critically on the quality and calibration of the printhead and head positioning mechanism. P-OLED displays must have a luminance variation of less than 5% across the display surface, which puts strict requirements on the jetting process and equipment. The aims and issues of jetting quality are summarized in Table 1.
In order to quantity the jetting quality, the drop velocity, volume and directionality are measured in-situ using a drop visualization system.

Table 1 Jetting Quality- Aims and Issues

Aims
1. Excellent drop volume uniformity ± 2%(Target)
2. Excellent drop directionality < ± 10 mrad (corresponding to a drop placement error of ± 5µm at 0.5mm head to substrate distance)
3. Excellent drop placement accuracy <± 15um
4. Short drop tails at 5-10ms velocity
5. Even nozzle plate wetting – minimise variations in placement
6. Clean break off with no satellites
Issues
1. Nozzle to Nozzle variation cause non-uniformity of drop volume
2. Directionality may be poor at high frequencies even when nozzle plate wetting is good
3. Tails can be longer than printhead to substrate throw distance
4. Poor nozzle plate wetting can lead to failure at frequencies ~5-10kHz
5. Polymers may fail at low jetting frequencies if viscosity or Mw high
6. At higher velocities drop tails may break up into Satellites

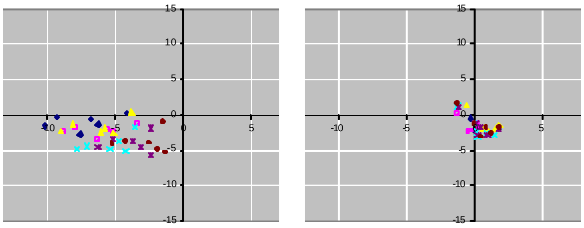
Directionality and velocity measurements are straightforward and can be measured up to ~ 10 kHz with new software and new optics system. Volume measurement is more problematic, especially for non circular drops. The jetting quality depends strongly on of the directionality and drop volume uniformity of the printhead nozzles. A few tens of picolitres (pl) must be deposited at each exact location on the substrate without overflowing and contaminating neighbouring pixels of different color. Variation in ink-drop volume may be perceived as brightness variation across the P-OLED display. "Driver Per Nozzle" DPN tuning has been developed by Litrex and Spectra inc. to adjust the dispense characteristics of each nozzle individually. The DPN control of velocity is more accurate and quicker than control of volume. In Fig. 5, a drop velocity uniformity of less than 3% is achieved by Litrex Corp using DPN technology.

Fig 5. Drop Velocity Variation after DPN Correction



The directionality is better than ±10mrad corresponding to a drop placement error of ± 5µm at 0.5mm head to substrate distance. CDT uses a Mitutoyo inspection system to analyse the placement of single drops in pixel wells. The drop placement accuracy has been significantly improved at CDT by stage mapping and software development. A drop placement accuracy of typically within ± 3 microns was achieved after these improvements, as shown in Fig. 6.

Fig 6. Improved Drop Placement by stage mapping & Correction in the Drop layout Software.


(a) Before ***(b) After***

3-3. High Performance Ink Jet Printer Development

A high performance ink jet printer for a low cost P-OLED manufacturing line must satisfy the following requirements; (1) mechanical accuracy for drop placement accuracy of ±15 microns (2) high through-put; 2 min TACT time (3) jetting reliability (4) low cost. The accuracy of the printer's X-Y positioning equipment plays a key role in determining the precision of ink drop placement. Litrex 140P printers are specified with drop placement accuracy of +15µm, 5.5 σ assuming drop deviation <10 mrad. This mechanical accuracy is not sufficient for high resolution display printing such as up to 200ppi. As shown above in Fig.6, CDT has achieved drop placement of ±3 microns by stage mapping and development of the drop layout software

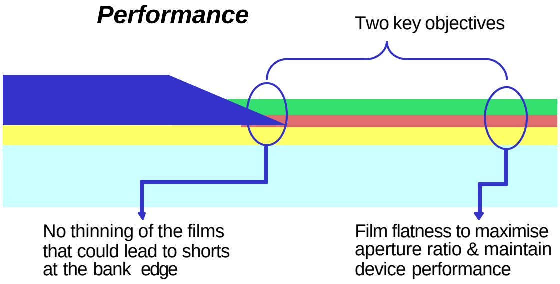
There are several ways to achieve high printing speed (high through-put); (1) Optimised ink formulation for jetting at high frequency (2) New printhead development capable of high frequency dispensing (3) Bi-directional printing scheme (4) Multiple printheads (4 to 24). In Gen.2 glass size, 2 min TACT can be achieved by 6 kHz printing for the HTL layer and 11kHz printing for the EL material. Litrex (a 50:50 joint venture between ULVAC and CDT) is developing a high performance ink jet printer with a modular design concept called the M-Series. The M-series can achieve 2 min TACT even though the glass size increases substantially from Gen.3 to Gen.7/8, by using multiple (2-24) printheads, bi-directional printing and implementing new printheads such as Spectra M-series/Xaar Omni.

For establishing low cost P-OLED manufacturing process technology, development of high performance ink jet printer with reliable and high through-put is essential. Litrex Corp. will continue to improve and develop ink jet equipment for P-OLED manufacturing lines. CDT continues to work closely with Litrex Corp. to improve the performance and reliability of IJP equipment, using its own P-OLED manufacturing line as a test bed. This line consists of 6 Litrex 140P systems which are installed at CDT's pilot R&D line(Godmanchester, UK).

3-4. Ink Jet Process Development

The complete P-OLED display fabrication process involves substrate pattering, cleaning, and surface treatment prior to LEP printing and subsequent cathode deposition and encapsulation. In order to have the "Right Device Performance" –and in addition to having low contamination (residual solvents, metals, plasma, etc.), the film should meet two key objectives after drying; (1) No thinning of the films that could leads to shorts at the bank edges (2) Good film flatness to maximize aperture ratio and maintain device performance as shown in Fig. 7.

Fig. 7 Two Key Objectives for Right Device Performance

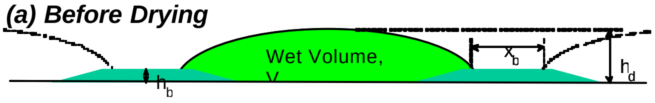


These two objectives requires development and optimisation of (1) Ink Formulation, as detailed in Section 3-1 (2) Bank Structure and pixel Design (2) Bank and anode surface treatment for reliable well filling (4) Drying/bake process optimization (4) Print strategy – drop positioning, interlacing, edge effects

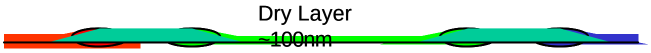
In order to make uniform flat film of hole transfer layer and LEP layers in the pixel, the bank design is very important. Fig. 8, illustrates the design challenges for the bank structure and pixel design. Confinement of the wet ink volume in the wells depends primarily on the surface treatment, but also on the bank architecture and ink formulation.

Fig.8 Bank Design Challenges for Device Optimization (a) Before Drying (b) After Drying

(a) Before Drying



(b) After Drying



The surface treatment on bank (Hydrophobic) and well in pixel (Hydrophilic) is essential for reliable well filling because the bank is not just mechanical container to hold ink within pixel well. Without proper surface treatment, wet ink can overspill if the bank height is not enough to hold ink. Plasma treatment using controlled gas mixtures is used for proper surface treatment. Special gas is used to increase the contact angles on bank resist compared to ITO as shown in Fig. 9. During optimization plasma treatment, surface contamination also needs to be considered.

Fig.9 The Contact Angle Change with Plasma Treatment Time.

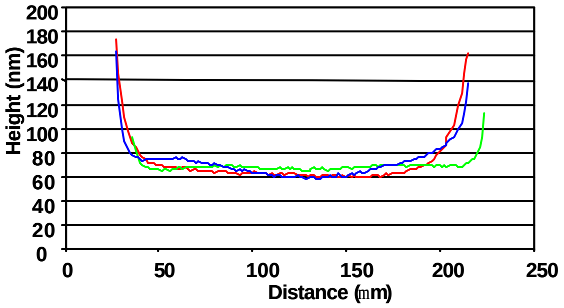
In order make high resolution displays, the bank structure design and surface treatment are very critical to improve drop placement accuracy because wet ink should repel from bank and move into the well even if the ink drops land on bank.

The drying/bake process is also very critical to get flat film formation from wet ink in pixel well. The smaller difference of dry process between first- and last-printed displays affects display non-uniformity. This has been achieved using a vacuum drying process. Vacuum is used to counter the coffee ring effect and also increases rate of drying to decrease TACT.

So, the dry and bake process need to be optimize to get good uniform of film thickness.

As shown in Fig. 10, the fat film formation is achieved by optimization of ink formulation, design of bank structure, surface treatment and drying/bake process optimization.

Fig. 10 The Flat Film Formation



CDT has demonstrated a 7" AM-PLED display with good brightness uniformity by optimising the inks, equipment and processes as discussed in this article.

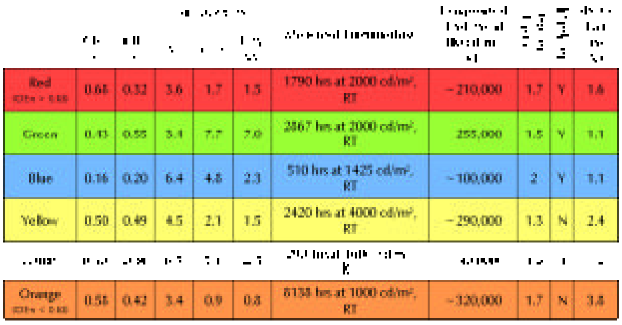
This display is shown in Fig. 11. This clearly demonstrates that an integrated strategy that optimises all aspects of the fabrication process is vital to achieve good device uniformity.

Fig. 11 7" AM-PLED display Produced at CDT's Technology Development Centre

4. CDT Fluorescent and Phosphorescent Material Performance.

The lifetime of Red and Green device has been acceptable for many applications for some time now. Until recently, the much shorter lifetime of blue has prohibited widespread use of FPD application. However, with an R&D program focussed on improving the understanding of the degradation mechanisms, the blue life time has been improved tremendously up to 100,000hr @ 100cd/m2.(Table 2).

Table 2. Summary of P-OLED Material Performance



[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Red [illegible]	0.68	0.32	3.6	1.7	1.5	1790 hrs at 2000 cd/m², RT	~ 210,000	1.7	Y	1.6
Green	0.43	0.55	3.4	7.7	7.0	2867 hrs at 2000 cd/m², RT	255,000	1.5	Y	1.1
Blue	0.16	0.20	6.4	4.8	2.3	510 hrs at 1425 cd/m², RT	~ 100,000	2	Y	1.1
Yellow	0.50	0.49	4.5	2.1	1.5	2420 hrs at 4000 cd/m², RT	~ 290,000	1.3	N	2.4
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Orange [illegible]	0.58	0.42	3.4	0.9	0.8	6138 hrs at 1000 cd/m², RT	~120,000	1.7	N	3.8

In 2005, CDT has roadmap to achieve Blue life time of 200,000hr, @ 100cd/m2. This fluorescence Blue life time corresponds to 8,000hr @ 500cd/m2. It will be enough life time & efficiency to launch TV products in 2006.

In Phosphorescent material development, we are working very closely with our material partner in Japan. The performance in terms of life time & efficiency of CDT's Phosphorescent materials has improved drastically based on material development know-how developed from its fluorescent material development programme.

5. Breakthrough/Challenge for Commercialization of P-OLED Display Technology.

Although there are several monochrome PLED products already in the marketplace, there are 3 challenges remaining for full commercialization of colour PLED technology; (1) Improvement of life time, color gamut and efficiency (2) Reliable/Manufacturable Ink Jet Process Development (3) High Performance Ink Jet Printer Development: The industry is continuing to develop P-OLED display performance and manufacturability to meet display makers' requirement for commercialization. Rapid progress has been made in recent years, and the blue lifetime is already sufficient for many applications. CDT plans to increase blue life time significantly by developing (1) New Material Development including New Hole Transport layers in-house and with external partners (2) Device Optimization such as top emission.

In terms of developing a reliable/manufacturable ink jet process, CDT has invested heavily in equipment, man-hours and facilities to develop ink jet printing technology for P-OLED display manufacturing the past five years. CDT currently has six fully operational ink jet printers in high class clean room facilities located at the Technology Development Centre(TDC) in Godmanchester, UK. CDT also has a large team of engineers solely developing ink jet technology for P-OLED commercialization.

In high performance ink jet printer development, Litrex Corp. which manufacturers ink jet printer specially designed for printing P-OLED displays, currently produces equipment capable of printing onto Gen.2 substrate (370mmx470mm). Litrex has shipped more than 30 of these 140P and 142P printers. Litrex is currently building Gen.4 (730mmx920mm) and Gen.7/8 (over 2000mmx2000mm) printers for shipping in 2Q/3Q, 2005. Demand for larger PLED display screen and reduced costs will ultimately drive increase in substrate sizes for PLED display manufacture – just as it has for TFT-LCDs.

OTB Engineering (Eindhoven, The Netherlands) is currently working with CDT to develop the first fully integrated and automated in-line PLED display production facility. The first system is being built for Innoled, a subsidiary of Eastgate Technology. The fab line integrates substrate patterning and pretreatment, four Litrex 142 ink jet printers, fast cathode deposition, and thin-film encapsulation processes. The facility does not require a clean room because each tool is enclosed in a clean-air cabinet, and facility will be capable of 2 min TACT at Gen.2 glass substrate.

6. Conclusion

P-OLED technology has already overcome many of the hurdles to mass manufacturing

(1) Material and device performance vastly improved
(2) Robust Ink Jet Printing Process being developed
(3) Reliability of IJP equipment being demonstrated
(4) Larger Ink Jet Printer (Gen.4~Gen.7) being developed.

The first commercial products from manufacturing facilities are expected in 2005.

7. Acknowledgement

We thank our collaborators at display makers and material makers to continue developing P-OLED display technology for commercialization.

8. Reference

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