

## Technical Challenges for Polymer OLED Display Manufacturing.

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### 1. Abstract

Since Samsung SDI and Sony started mass production of AM-OLED display for mobile/TV applications, OLED technology has emerged as leading candidate among the many technologies under development for next generation Flat panel displays.

P-OLED (Polymer Organic Lighting Emitting Diode) technology, a class of OLED, is gathering momentum towards commercialization. P-OLED technology has made tremendous progress in terms of display performance (including life time, efficiency and color gamut) and in the maturity of ink jet printing process and equipment. In order to get into the mobile/TV application 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 PrintingTechnology". P-OLED technology has already overcome many of the hurdles to mass manufacturing.

In this paper, the latest developments in ink jet printing technology, including P-OLED material performance, is discussed.

### 2. Introduction

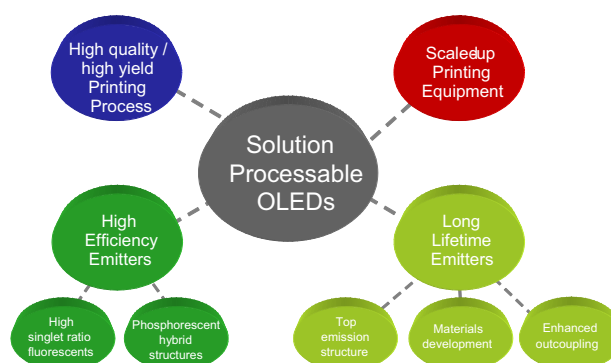
P-OLED technology provides an alternative to TFT-LCD for many display applications, and is particularly attractive in terms of its brightness, wide viewing angle, fast response time and low power consumption. Since 2002, several companies such as TMD (Toshiba-Matsushita Display), DuPont, Seiko-Epson, Casio, Samsung Electronics, Sharp, and CDT have been developing AM-PLED 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.<sup>[1] [2] [3]</sup>

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 \$1.1 billion in 2008 and \$1.7 billion in 2009<sup>[4]</sup>, requiring rapid progress in volume production methods and

processes. Mobile phones, MP3 player, PMP, automotive and industrial applications will drive the growth in OLED markets through 2008. OLED manufacturing costs will become competitive with a-Si TFT LCD in small/medium display applications if manufacturing factors such as TACT, material utilization and equipment utilization are optimised.

In order to penetrate the OLED market successfully, P-OLED display technology must meet the following display makers' requirements in terms of lifetime, efficiency, color coordinates and manufacturing cost

**Fig. 1 Development across all Technology Fields**



In this paper, we give an update on developments by CDT and Sumitomo Chemical in the area of light emitting polymer (LEP) materials and summarise the rapid advances in manufacturing processes used for solution processable P-OLEDs (Fig.1).

### 3. P-OLED Material Performance.

Since the formation of Sumation, a JV between CDT and Sumitomo Chemical, P-OLED technology has made tremendous progress in terms of display performance (including life time, efficiency and color gamut). The lifetimes of Red and Green materials have been acceptable for many applications for some time now. Until recently, the much shorter lifetime of blue prohibited widespread use of PLED in FPD applications. However, with an R&D program focussed on improving the understanding of PLED degradation mechanisms, the blue T50 life time has been improved tremendously and currently stands at 18,000hr@1000cd/m<sup>2</sup>. (Table 1).

**Table 1. Summary of P-OLED Material Performance**

Colour	Colour CIE (at 100cd/m <sup>2</sup> )	Efficiency (cd/A at 1000cd/m <sup>2</sup> )	T <sub>50</sub> LT from 1000cd/ m <sup>2</sup> (hrs)	Driving Voltage	Acc Factor
Red	(0.63,0.37)	30	> 200K	5.0 (0.8*)	2
Green	(0.29,0.64)	18	80K	4.4 (0.5*)	1.9
Blue	(0.14,0.18)	12	18K	4.0 (0.5)	2
White	(0.34,0.39)	12	8K	4.4 (0.5*)	1.8

- V at end of test at 1000cd/m<sup>2</sup> (V)

- Bracketed values show dV over lifetime (V)

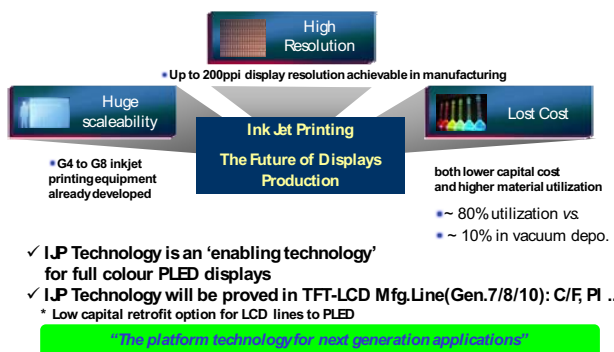
\* predicted

The performance in terms of life time and efficiency of phosphorescent Red materials has improved drastically based on material development know-how developed as part of a fluorescent material development programme. Sumation has a roadmap to achieve material performance targets that will meet product specifications for large TV applications in 2009.

#### 4. Low Cost Manufacturing Process Technology; Solution Processable Printing Technology

CDT has been developing "Inkjet Printing Technology" for several years because it offers a potential route to lower manufacturing costs compared to vacuum processed OLEDs. One attractive characteristic of P-OLEDs is that they are solution-processable unlike the vacuum-deposited material used to fabricate small molecule-OLED (SM-OLED) displays. Ink jet printing (IJP) of P-OLED devices has several benefits from a manufacturing perspective, including scalability to Gen.7/8/10 and the possibility to print high resolution displays (Fig.2). However, there are still challenges to be overcome in terms of printed P-OLED displays, including:

- (1) TACT Time
- (2) Lifetime of printed displays
- (3) Display Non-Uniformities
- (4) High Reliability/High Process Yield

**Fig.2 Advantages of Ink Jet Printing Technology**

#### 4.1. TACT Time Improvement

There are several ways to achieve high printing speed (high through-put); (1) Optimised ink formulation for jetting at high frequency (2) New print head development capable of high frequency dispensing (3) Bi-directional printing schemes (4) Multiple printheads (4 to 48). For Gen.2 glass size, a 2 min TACT can be achieved using 6 kHz printing for the HTL layer and 11 kHz printing for the EL material. Litrex (a 100% subsidiary of ULVAC) is developing a high performance ink jet printer with a modular design concept called the M-Series. The M-series can achieve a 2 min. TACT even with an increase in glass size from Gen.4 to Gen.7, 8, or 10 by using multiple (2-48) print heads and implementing new print head designs such as those being introduced by Diamatix, Xaar, and Konica-Minolta.

#### 4.2. Performance Gap between IJP and Spin-coated Devices.

Ink jet printed devices currently do not have the same level of performance spin-coated devices. Several factors were identified which contribute to reduced printed device lifetimes. These include:

1. HIL ink formulation
2. The solvents used to formulate the LEP ink
3. Poor interlayer film formation
4. Incomplete cross-linking of the interlayer resulting in mixing of materials when the LEP layer is printed
5. Polymer sensitivity to air, light and temperature during printing and processing

While the impact of each factor varied slightly for each LEP formulation, the factors were common and followed similar trends for R, G, and B. HIL formulation and IL process improvements led to significant increase in printed lifetime with respect to equivalent spin-coated devices. Lifetime and efficiency of printed devices is now close to what is expected based on the performance of spin-coated devices.

#### 4.3. Display Non-Uniformity: Pixel & Panel Non-Uniformity

The inkjet printing process can lead to artefacts in the finished display panel which are caused by inconsistencies in the wetting, spreading and drying processes of inks on the substrate. Artefacts include:

1. Non-flat or non-uniform films
2. Coffee ring effect
3. Doming
4. Swathe Joins
5. Incomplete pixel wetting

The drying conditions are a critical parameter governing flat film formation after ink is deposited in

pixels and the solvent begins to evaporate. Drying is optimised to ensure that films are flat (to maximise emission area and lifetime) and to reduce swathe joins (necessary when multiple print head passes over the substrate are required to coat a large display). Typical swathe joins are shown in Fig. 3. These are removed by careful ink formulation and via print process optimisation.

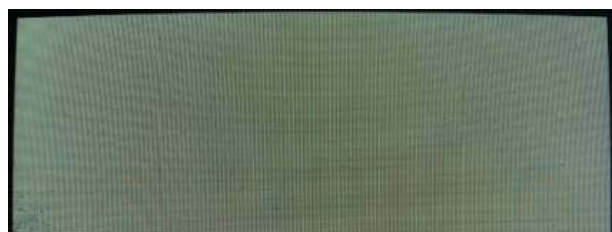
**Fig. 3 Display Non-Uniformity caused by Swathe Joins**

**(a) Un-Optimized Ink Formulation & Printing Strategy**



Swathe joins

**(b) Improved Ink Formulation & Printing Strategy**



CDT has demonstrated a 14" AM-PLED display (Fig.4) with good brightness uniformity by optimising inks, equipment, and printing and drying processes.

**Fig. 4 14"AM-PLED Display Produced at CDT's Technology Development Centre**

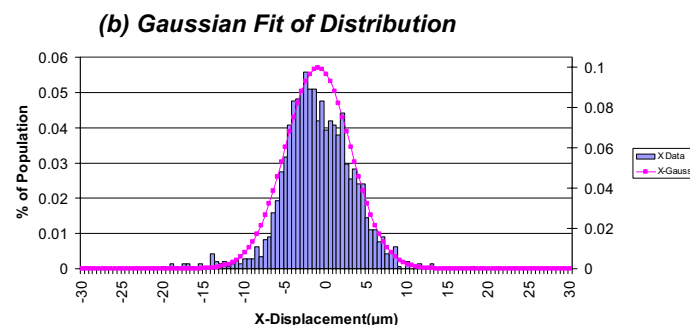
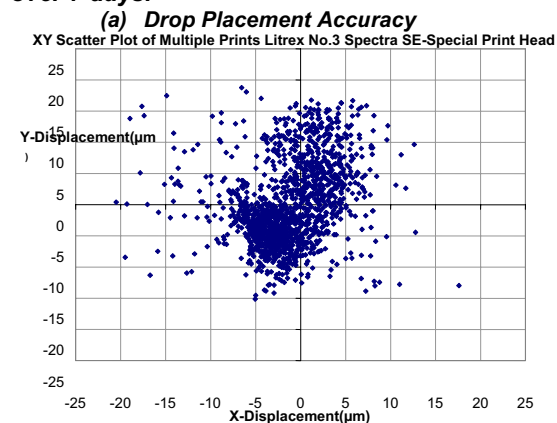


#### 4.4. High Reliability/High Process Yield

In order to be suitable for volume manufacturing, ink jet printing technology has to be highly reliable (reliable jetting at high frequency) and be capable of achieving high process yields (drop placement accuracy). The formulated ink should be capable of jetting at over 10 kHz with high reliability to achieve high through-put in a manufacturing line. Ink drops must also have the appropriate speed and drop shape as they are ejected from the nozzle and travel toward the substrate. The drop characteristics are assessed using a high speed camera and stroboscopic illumination, and optimised by adjusting the piezo drive waveform that controls each nozzle in the print head. Developments in IJP head design have enabled stable and reliable printing of a wide range of polymer inks at increasingly high frequencies.

The reproducibility of drop placement will be critical for any P-OLED manufacturing line. Fig. 5 shows a composite of multiple runs over a period of 7 days with a well maintained head at correct head angle. Gaussian fit of distribution gives a one sigma of 4µm. Errors in directionality are mainly caused by manufacturing defects in the nozzles, uneven wetting of the nozzle plate, poor drop break off and low droplet velocity.

**Fig. 5 Reproducibility of Drop Placement Accuracy over 7 days.**



New print heads which incorporate non-wetting coatings on nozzle plates and which dispense smaller drop volumes will be required to further improve drop placement accuracy as shown in Table 2. In order to make high resolution displays with > 200ppi resolution, print heads with small drop volume (<5pl), excellent directionality (<10mrad: corresponding to a drop placement error of  $\pm 5\mu\text{m}$  at 0.5mm head to substrate distance) and non-wetting coating are necessary.

**Table 2 Jetting Quality- Aims and Issues**

<b>Aims</b>
1. Excellent drop volume uniformity $\pm 2\%$ (Target)
2. Excellent drop directionality $< \pm 10 \text{ mrad}$ (corresponding to a drop placement error of $\pm 5\mu\text{m}$ at 0.5mm head to substrate distance)
3. Excellent drop placement accuracy $< \pm 15\mu\text{m}$
4. Short drop tails
5. Even nozzle plate wetting – minimise variations in placement
6. Clean break off with no satellites
<b>Issues</b>
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

Diamatix's next generation print head, the M-series, has a nozzle plate manufactured from silicon using a MEMS process. This head will offer many more benefits for drop placement accuracy, smaller drop volume and jetting reliability. Xaar (Cambridge, UK) is developing a 1000-nozzle print head based on their proprietary "Side Shooter" technology. Each nozzle will be individually tuneable and capable of variable-drop – size dispensing, based on a 5pl drop volume with eight or more levels of gray scale.

Konica has developed a print head capable of dispensing drops with volumes down to 7pl, a figure that can be reduced to 5 pl by utilizing DPN nozzle tuning.

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

There are 3 challenges remaining for volume commercialization of PLED technology, namely: (1) Improvement of life time, color gamut and efficiency, (2) Development of reliable/manufacturable ink jet processes (3) Development of high performance ink jet printing equipment:

The industry is continuing to develop P-OLED technology and progress has been made towards a demonstrating the viability of mass manufacturing of full color PLED devices. Rapid progress has been made in recent years, and the blue lifetime is already sufficient for many applications. Sumation will continue to develop improved materials and CDT is actively developing new device structures with improved performance, e.g. top emission structures.

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

Since Litrex Corp (now a 100% subsidiary of ULVAC) produced high accuracy printers for P-OLED applications, there has been a proliferation of equipment companies developing high performance ink jet printers for TFT-LCD applications, e.g. printers are now being used for depositing alignment layer and color filters in Gen.7/8/10 LCD production line. High performance printing technology is maturing and many of the printers developed for LCD will also be suitable for P-OLED applications.

## 6. Conclusion

P-OLED technology has already overcome many of the hurdles encountered on the route to mass manufacturing:

- (1) Material and device performance has been dramatically improved
- (2) IJP deposition technology has matured and is becoming increasingly accepted
- (3) Robust print processes have been developed
- (4) Reliability of IJP equipment has been demonstrated
- (5) Routes to printing on larger substrates is now clear
- (6) Solution processing has been shown to be an attractive and cost effective route to volume manufacturing

The first commercial products from ink jet based manufacturing processes are expected in 2010.

## **7. Acknowledgement**

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

## **8. Reference**

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