Scaleable, Cost Effective Display Manufacturing Technology Based on White OLED

James R. Buntaine[1] and G. Rajeswaran[2]
[1]Display Business, Eastman Kodak Company, Rochester, NY, 14625 U.S.A.
TEL:+1-585-477-3730, e-mail: james.buntaine@kodak.com
[2]OLED Systems, Eastman Kodak Company & Kodak Japan Ltd., Tokyo, Japan

Keywords : List White OLED Manufacturing Scaleable Cost

Abstract

The AMOLED industry must compete with AMLCD displays by standardizing around scaleable technology platforms that deliver display-performance and manufacturing-cost goals. Kodak White OLED device architectures have the potential to achieve the best performance and cost tradeoffs. Here we describe the building blocks necessary for delivering effective AMOLED mass production technologies.

1. Introduction

At the SID 2000 conference, a joint team from Kodak and Sanyo Electric demonstrated the first full color AMOLED displays [1] by combining low temperature poly-silicon (LTPS) substrates with red, green and blue OLED emitters patterned by precision shadow masks. These AMOLED displays caused major excitement in the display community and launched several display development programs in laboratories worldwide. Subsequently, Kodak and Sanyo formed the joint venture company in 2001, SK Display Corporation, in order to manufacture AMOLED products. The first AMOLED product from SK Display was incorporated into a Kodak digital camera (Model LS633) in 2003.

2. First Generation OLED Manufacturing

First generation OLED manufacturing technologies were used in the manufacture of these first products at SK Display, namely, cluster type vacuum deposition systems, precision shadow masks for red, green and blue OLED emitter patterning, early versions of Kodak's linear source technologies [2], etc. This manufacturing experience provided Kodak with deep insight into the factors governing manufacturability and cost. These first generation cost factors and the countermeasures incorporated in second-generation OLED manufacturing technologies are the topics of this paper.

Arguably, the most important factor that will determine whether AMOLED displays are widely adopted is unit-manufacturing cost (UMC). It has been recognized that direct emitter patterning by precision shadow masking is costly as well as cumbersome and probably not scaleable to larger glass sizes due to thermal expansion issues. Additionally, the yield is likely to be negatively impacted by the direct contact of the shadow mask to the AMOLED substrates. Prior to Kodak's SK Display mass production experience in 2002, it was thought that state-of-the-art low temperature poly-silicon (LTPS) thin-film transistor (TFT) substrates prepared by excimer laser annealing would be directly suitable for OLED applications. However, AMOLED applications were seen to be highly sensitive to small threshold voltage non-uniformities in the current driving thin film transistors. The impact on the display was frequent, objectionable visual muras that drove low manufacturing yield.

The overall impact on the UMC of first generation AMOLED displays can be understood in terms of the impact on variable and fixed cost factors. Tables 1-1 and 1-2 describe the top cost factors, variable and fixed costs respectively, that were encountered in SK Display's first generation AMOLED manufacturing.

Several independent strategies were needed to tackle LTPS costs due to mura yield losses, OLED materials costs due to poor materials utilization, cap glass costs resulting from specialized pocketed glass substrates and driver IC costs. In addition, it was also clear from the above experience that color patterning processes significantly impact productivity, yield and scalability resulting in highly unfavorable manufacturing costs compared to equivalent AMLCD displays, and must be dealt with in order to establish an AMOLED display business.

Table 1-1: Top 5 Variable Cost Items
(First Generation AMOLED Manufacturing)

Item	Cost factors
LTPS	CMOS needs 9 mask levels, Limited to Gen 4 size, Yield loss (defects caused by visual mura)
OLED Materials	Point Source or Linear Source with Cluster Type Deposition Systems result in poor material utilization
Precision Shadow Masks	Cost issues, Scalability issues, Yield loss (defects caused by mask contact)
Cap Glass	Pocketed glass for desiccant is a specialty item
Driver IC	Larger die size for AMOLED compared to equivalent LCD displays

Table 1-2: Top Fixed Cost Items
(First Generation AMOLED Manufacturing)

Item	Cost factors
Productivity	High TAKT time (caused by robot handling and precision mask alignment steps) in cluster type OLED deposition systems
Yield	LTPS muras and mask contact defects adversely impacts yield
Scalability	Precision shadow-mask patterning process limitation of < ½ Gen 4 size results in significant additional capital

This prompted Kodak and Sanyo Electric teams to investigate two alternate color patterning technologies for use in manufacturing, namely, a) RGB emitter layer patterning by maskless laser transfer methods (also known as Radiation Induced Thermal Transfer or RIST) and b) uniform white OLED emitters deposited over RGB color filters integrated on LTPS substrates.

Although the maskless laser transfer color patterning resulted in excellent high resolution patterning under vacuum environment (compatible with OLED deposition processes) [3], the lifetime of resulting OLED R, G and B devices were lower than equivalent vacuum evaporated control samples. The laser transfer method resulted in material specific narrow process windows and required extensive process re-optimization whenever device formulations were improved. In addition, our preliminary analysis indicated that the additional steps of donor preparation and laser writers would increase manufacturing costs. For these reasons, the focus was made on white OLED technology as the viable alternative to precision shadow mask technology.

Kodak and Sanyo activities on W-OLED emitters with RGB color filters resulted in the initial demonstration of a 14.7" full color display at CEATEC in 2002 [4]. In this bottom-emission format the white OLED emitter is applied across the entire display surface and the R, G and B emission results from the color filter array that is formed on the LTPS substrate prior to OLED deposition, as shown in Fig.1 below.

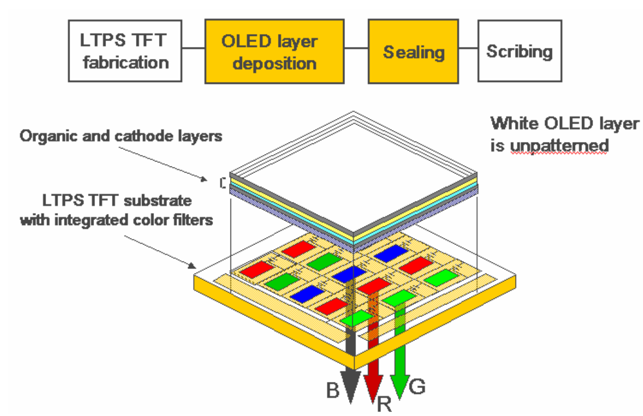

Fig.1: Concept of AMOLED display with W-RGB format

Full color displays are easily fabricated by the above method. However, the power consumption of this format is too high as a consequence of over 70% of the white OLED emission being absorbed by the color filters. In order to overcome this problem, Kodak developed RGBW format architecture, as shown in Fig.2, that reduces power consumption significantly [5],

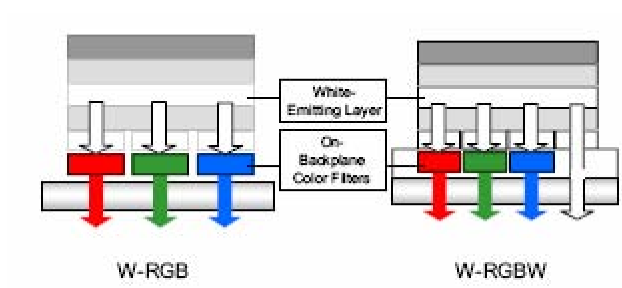

Fig.2: Concept of W-RGBW display

In 2006, Sanyo introduced a digital video camera (Model Xacti HD) product containing an AMOLED display based on the W-RGBW format. Widespread adoption of W-RGBW AMOLED display technology depends on continued progress in the performance of white OLED devices, their functional materials and matched color filter sub-technologies. These key building blocks serve as enabling engines for the delivery of AMOLED display performance comparable or exceeding equivalent LCD displays. In this pursuit, there have been significant advances at Kodak in white OLED materials and devices [6-8].

3. Second Generation OLED Manufacturing

In this section, we will describe countermeasures to reduce or eliminate each of the high cost items shown in Tables 1-1 and 1-2.

a) As a first common countermeasure, OLED manufacturing must adopt a maskless color patterning technology. Kodak's choice of the maskless white OLED format for manufacturing overcomes several precision shadow mask limitations, including: alignment time, defects caused by mask contact to the substrate, cost of the masks and their cleaning, and the inherent non-scalability to larger than Gen 4 sizes. Results include productivity improvement through TACT time reduction; yield improvement through defect reduction, and scaleable (Gen 4+) OLED manufacturing systems.

W-RGBW format does require the use of a color filter array and the color filter costs are comparable to equivalent LCD displays. However, the precision shadow mask is eliminated and the OLED manufacturing operation can leverage a mature color filter technology that is widely in use for LCD.

b) As a second common countermeasure, OLED manufacturing must adopt next generation materials delivery systems (evaporation sources) whose material utilization rates are high and performance under manufacturing environment is robust.

In the quest for efficient second-generation OLED manufacturing enablers, Kodak has developed improved OLED deposition technology[9] labeled Kodak Vapor Injection Source (KVIS). These sources enable OLED material usage efficiencies that are greater than 50%. KVIS also incorporates novel technology allowing for the introduction of multiple materials into the same manifold. The KVIS flash evaporator exposes materials to elevated temperatures only for times measured in seconds or sub-seconds. As such, whole new classes of materials, previously unusable due to source limitations, can now be used in OLED production. Kodak's strategic partners are now preparing to incorporate KVIS technology in their second generation OLED manufacturing equipment [10, 11]

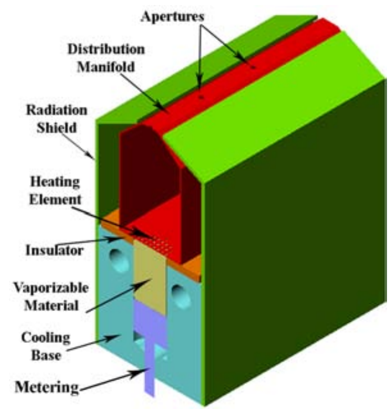

Fig.3. Concept of Kodak Vapor Injection Source (KVIS)

c) As a third common countermeasure, yield losses due to LTPS substrate non-uniformities must be eliminated. Excimer laser-annealed LTPS TFT substrates have the advantage of excellent device stability, but require additional manufacturing steps such as excimer laser annealing, ion doping and activation resulting in higher intrinsic production costs. Such additional costs are usually offset by additional levels of device integration that becomes possible with the advanced features of LTPS TFT devices.

Further refinement of the early version of the mura-free technology at Kodak has resulted in the development of Global Mura Compensation (GMC) technology [12]. This has been shown to reduce LTPS muras to a level far below that of visual perception (in gray fields). Over the past 3 years, Kodak has evaluated LTPS substrates from several partner companies and ensured that GMC technology is universally applicable in all these cases. Fig.4 shows successful examples of GMC technology applied to LTPS substrates and AMOLED displays manufactured on these LTPS substrates.

As a general trend, LTPS designs for AMOLED displays are adopting PMOS rather than CMOS so that the number of mask levels becomes comparable to a-Si designs. In addition, discrete electronics are tending to chip-on-glass (COG) designs to minimize costs further. Fig.5 shows the high level specifications of a pre-commercial Kodak AMOLED product that integrates the GMC and COG technology progress to date to achieve an optimal performance-cost tradeoff.

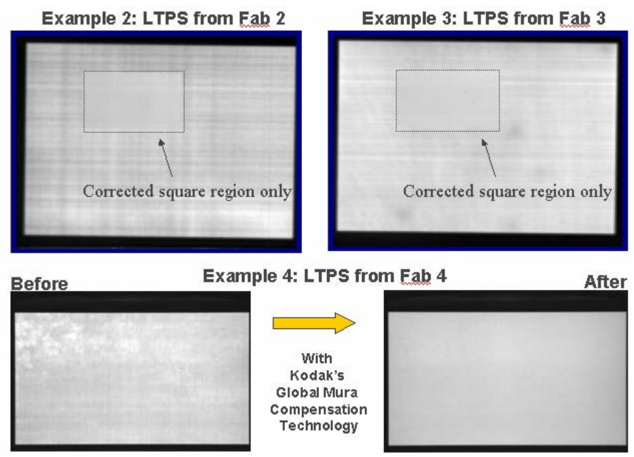

Fig.4: Examples of Kodak's Global Mura Compensation Technology

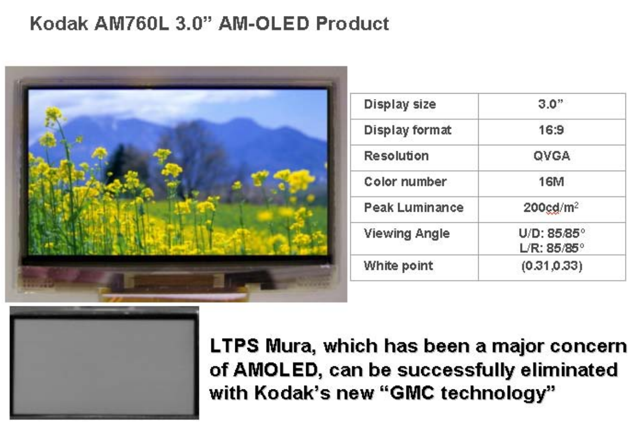

Fig.5: Kodak's AM760L 3.0" AMOLED pre-commercial product with GMC technology and COG implementation

For the future, TFT substrate cost structure must be comparable with equivalent LCD display TFT. Amorphous silicon (a-Si) TFT substrates have the lowest cost structure, but these have the limitation of unstable TFT threshold voltage over the life of the device. LTPS substrates prepared by non-laser annealing methods offer the promise of eliminating visual muras, but the technology is yet unproven in a production environment. Ultimately, TFT substrates with the cost structure approximating a-Si substrates will be necessary to be cost advantaged.

d) As a fourth common countermeasure, the selection of a maskless color patterning technology, such as the white OLED technology, enables an "in-line" production machine design, where each layer requires only one source and the substrate glass is transported above the source assembly in one pass, to deposit all of the organic layers required in the OLED structure. With the white OLED format, there is no need to stop to change masks during the OLED deposition operation, reducing the TACT time required. Thus the deposition tool size and complexity are minimized, and the result is a cost-effective manufacturing system. This second-generation OLED production equipment will become available in 2008.

4. Summary

Based upon the past experience of Kodak by itself and with its joint-venture partner Sanyo Electric, Kodak has selected and developed an ensemble of manufacturing technologies that can be integrated together to provide for low-cost AMOLED panel production. The ensemble of manufacturing technologies include the elimination of precision shadow masks, elimination of operations that do not cost-effectively scale beyond Gen 4 mother glass size, the invention of a new KVIS source technology with high material utilization process, the creation of a 2-min TACT time process flow, and power efficient white OLED architectures. In the past year, Kodak teams have been verifying the performance of these integrated manufacturing concepts at a pilot line in Japan in collaboration with ULVAC. These new manufacturing technologies will serve the OLED industry well in the coming years.

Tables 2-1 and 2-2 provide a summary of the countermeasures described in this paper that are utilized in second generation OLED manufacturing to overcome the current limitations seen in first generation OLED manufacturing.

Table 2-1: Top 5 Variable Cost Engineering Solutions (Second Generation AMOLED Manufacturing)

Item	Engineering Solutions
LTPS	PMOS needs 6 mask levels only, ELA LTPS for < Gen 4 with Global Mura Compensation (GMC) technology from Kodak, Non-laser LTPS for all glass sizes
OLED Materials	Kodak Vapor Injection Source (KVIS) injectors with linear or area manifolds; quick turn on / turn off source technology
Precision Shadow Masks	Eliminate shadow masks by adopting W-RGBW technology (bottom or top emitting formats as needed in product designs)
Cap Glass	Incorporate desiccant free encapsulation technologies
Driver IC	New architectures capable of using sub-micron design rules will reduce die size

Table 2-2: Top Fixed Cost Engineering Solutions (Second Generation AMOLED Manufacturing)

Item	Engineering Solutions
Productivity	Migrate to In-line OLED deposition systems that eliminate robot handling & precision mask alignment steps. TACT time goal (2008) = 2 min
Yield	Combination of Kodak's GMC and maskless white OLED technologies
Scalability	Combination of Kodak's KVIS injector technology, maskless white OLED technologies and In-line production systems (horizontal or vertical orientation)

5. References

1. G. Rajeswaran, M. Itoh, M. Boroson, S. Barry, T.K. Hatwar, K.B. Kahen, K. Yoneda, R. Yokoyama, T. Yamada, N. Komiya, H. Kanno and H. Takahashi, SID'00 Digest, p.974, 2000.
2. S.A. Van Slyke, A. Pignata, D. Freeman, N. Redden, D. Waters, H. Kikuchi, T. Negishi, H. Kanno, SID'02 Digest, p.886, 2002.
3. M. Boroson et al., SID'05 Digest, p.972, 2005.
4. K. Mameno et al., Abstract G-06, The 8th IUMRS Int. Conf. on Electronic Materials, June 10-14, 2002.
5. A. Arnold, T.K. Hatwar, M. Hettel, P. Kane, M. Miller, M. Murdoch, J.P. Spindler and S.A. Van Slyke, Proc. of IMID'04, p.809, 2004.
6. T.K. Hatwar, J.P. Spindler and S.A. Van Slyke, IMID/IDMC'06 Digest, p.1577, 2006.
7. T.K. Hatwar, J.P. Spinder and S.A. Van Slyke, SID'06 Digest, p.1964, 2006.
8. J.P. Spindler and T.K. Hatwar, SID'07 Digest, p.89, 2007.
9. M.Long et al, SID'06 Digest, p.1474, 2006.
10. T. Negishi, Finetech Japan 2007, Tokyo, April 2007.
11. B. van Rens, OLEDs Asia 2006, Singapore, April 2006.
12. T. Tsujimura, OLEDs Asia 2006, Singapore, April 2006.