The Challenges of Flexible OLED Display Development

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Abstract

Flexible OLED display would be one of the most popular display type in the future. However there are many challenges before the mass production ability matured. Flexible substrate preparation, Lower temperature w/ LTPS (L-LTPS), thin film encapsulation and flexible module process are discussed separately in this paper. The difficulties of each process were pointed out and provide some solution for reference. We improve and apply the solution in our 4.35"~10.9" flexible OLED sample.

Author Keywords

Flexible display, OLED, organic light-emitting diode, Lower temperature w/ LTPS, TFE

1. Introduction

As the TFT-LCD technology improved, the well-know merit of OLED display like wide view angle, fast response time, high purity of RGB color, lower power consume already become similar with TFT-LCD. The remained one unique character of OLED display is good for flexible product. Because of back light unit construction and cell gap control limitation, TFT-LCD product is very difficult to be a real flexible display.

In pass several years, the market share of small size OLED display in mobile market increased gradually. The next engine to push OLED market share increasing will be the flexible OLED display. The main stream of the OLED display is rigid type and curved type. The rigid type constructed by two glasses, one is LTPS-TFT glass which contain TFT circuit and OLED device, another one is cover glass which can be integrated the touch panel function in it. The two glasses are sealed by laser frit process. The curved type is made up by flexible substrate, the LTPS circuit, OLED device and thin film encapsulation (TFE) are processed on the substrate step by step. Finally the flexible substrate laminated on a fixed curved cover glass. Although the substrate is flexible but final product is rigid like.

Almost all people expect a real foldable product come out as soon as possible and users can change the display area as they like. Before make it come true, several key and complex process of flexible OLED display must be overcome. Flexible substrate preparation, Lower temperature w/ LTPS (L-LTPS), thin film encapsulation and flexible module process are discussed separately in this paper

2. Key process of flexible OLED display

2.1 Plastic substrate preparation

Substrate is the essential difference between the flexible and rigid OLED. There are several materials being discussed for the flexible OLED substrate, and recently the strongest candidate is polyimide (PI), especially in the LTPS process which is the main method in small and medium size OLED. The LTPS process temperature is above 400℃, better heat resistance and dimensional stability of the substrate is considered.

One of drawbacks of PI is yellowish, which limited the applications in bottom-emission OLED. For this issue, the colorless PI, which is still with large coefficient of thermal expansion (CTE) and retardation problem, is under development.

Another drawback of PI is high water vapor transfer rate (WVTR), it's the common issue in polymer material. The moisture will pass through the polymer layer to interrupt the TFT characteristics and even more to downgrade the OLED performance. Sandwich structure like polyimide substrate / Inorganic material / polyimide substrate, this kind of stacked structure was tested. The sandwich substrate exhibits lower WVTR and lower thermal expansion than single layer PI substrate. In 60 °C / 90% RH storage lifetime test, the flexible AMOLED with sandwich substrate showed better HTHH reliability. No new dark spot was observed in AA area after 384 hours in the AMOLED sample with sandwich substrate, and only one dark observed in the border after 500 hours was attributed to the failure of side encapsulation. In contrast, a lot of new dark spots were observed in AA area with single layer substrate in the same test condition. Another significant difference is the dimensional stability. From the TMA result in Figure 1, it is clear that the sandwich substrate exhibited lower coefficient thermal expansion (CTE) than single layer substrate in high temperature. Glass is widely considered as the best substrate for LTPS process due to its low CTE and excellent heat resistance. The CTE of sandwich substrate is close to glass, which indicated better compatibility for large generation LTPS drive backplane manufacture process for lower warpage and lower total pitch variation (TPV). More detail items were disclosed in our team's another paper [1].

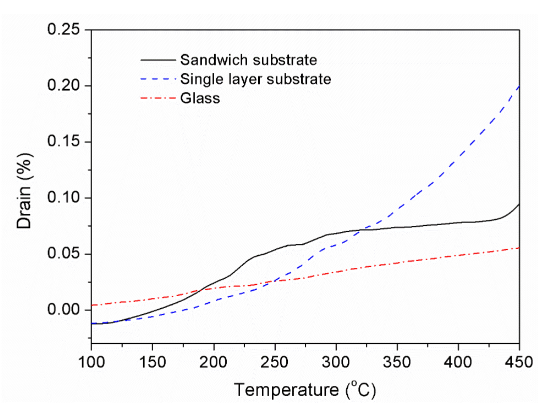


Figure 1. The dimensional stability of flexible substrate

 ISSN 0097-996X/17/4702-1034-$1.00

Most popular method to make up PI substrate is that coat liquid PI on glass surface and cure it with high temperature to transfer it to the solid PI. Sometimes laminate the PI film directly on the glass surface is an easier and faster way. But first method can solve lots of problem such as adhesive outgas、uneven surface in lamination. The challenge in PI coating process is the fume, particle and bubble issue accompany by the coating and curing process. These issues can be improved by modifying the process parameter and design a suitable process flow like queue time control of each step and optima the vacuum dry and heat curing process.

2.2 Lower temperature w/ LTPS (L-LTPS)

Flexible LTPS OLED back panel process can only use low anneal temperature (<450℃) because of the PI substrate material. First, a layer of plastic material (PI) was over coated onto a carrier glass to serve as the substrate. The PI film will be delaminated from the carrier glass after array process, to make flexible display. To avoid contamination and damage from the following crystallization process, buffer layers of SiNx and SiOx were deposited on PI substrate use Plasma Enhanced Chemical Vapor Deposition (PECVD) method. A layer of a-Si film was then deposited and crystallized by excimer laser annealing (ELA) to serve as the poly-Si channel layer. After gate-insulator (GI) deposition, Molybdenum was sputtered and pattern to sever as the gate. Followed by P+ implantation, the source/drain junction region was formed. After inter layer dielectric (ILD) deposition, an annealing less than 450 degree-C was then carried out to activate the implanted dopants and enhance the TFT characteristics. Contacts and source/drain electrodes were then formed by metal layer. The resulting TFT structure is illustrated in Fig. 2.

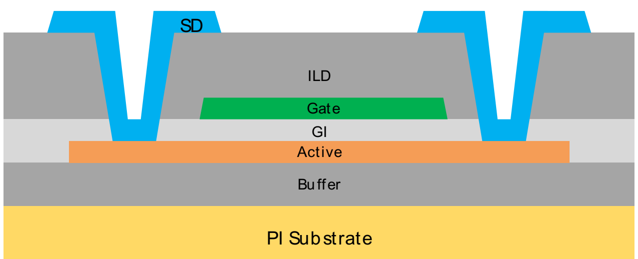


Figure 2. Illustration of a P-type TFT structure

Because of the PI flexible substrates, the maximum TFT annealing temperature is lower that PI materials limitation, which is less than 450 degree-C. But as glass substrates, the maximum TFT annealing temperature is 600 degree-C. Table 1 show the electrical characteristics and Figure 3 show the Id-Vg curves of the p-type TFTs, which are characterized at drain voltage of 0.1 V and 10 V, respectively, the size of PTFT is 3μm / 3μm, with high anneal temperature on glass substrate and low anneal temperature on flexible substrate. The results show the TFTs with low anneal temperature on flexible substrate, have slight smaller on-current, bigger off-current, and threshold voltage, low mobility. And the Ion/Ioff ratio is about one fifth than high anneal temperature on glass substrate. The different of the TFT electrical characteristics can be ascribed to the different anneal temperature.

Table 1. Characteristics comparisons of TFTs with high anneal temperature on glass substrate and low anneal temperature on flexible substrate.

TFT characteristics	Ion (A)	Ioff (A)	Vth (V)	Mob (cm2/Vs)	S.S. (V/dec)
High Anneal Temperature	1.97E-05	3.42E-11	-1.60	110	0.24
Low Anneal Temperature	1.60E-05	1.53E-10	-3.20	97	0.33

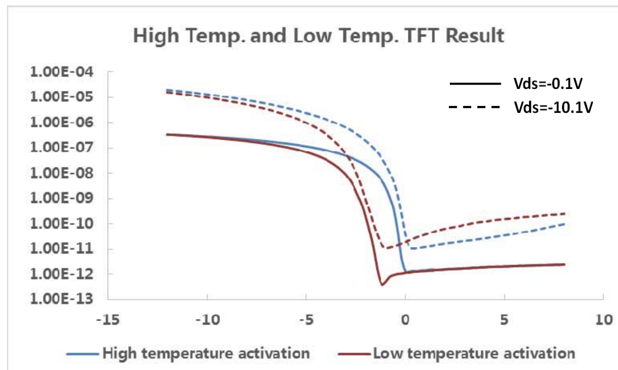


Figure 3. Id-Vg curves of the p-type TFTs, which are characterized at drain voltage of 0.1 V and 10 V, respectively, the size of PTFT is 3μm / 3μm, with high anneal temperature on glass substrate and low anneal temperature on flexible substrate.

Further, the Negative Bias Thermal Stress (NBTS) test was applied to LTPS TFT with high anneal temperature on glass substrate and low anneal temperature on flexible substrate to verify the electrical reliability. The conditions of NBTS are -30V on gate voltage, temperature is 60 degree-C and stress 7200 seconds and the result shows in Fig. 3. With low anneal temperature on flexible substrate, LTPS TFT NBTS Vth shift is -0.47V, but with high anneal temperature on glass substrate, the Vth shift is only -0.27V. It shows that TFT electrical reliability on flexible substrate is worse than on glass, some long time operation problems may cause from this issue.

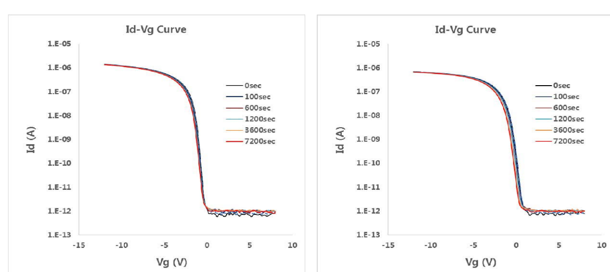
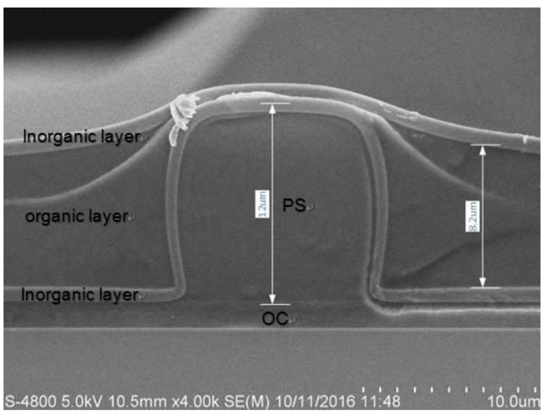


Figure 3. The stability of LTPS-TFT with NBTS test on glass substrate (a) and on flexible substrate (b), W/L=3/3NBTS: Vg=-30V, Vd=0V, Temp=60℃

2.3 Thin Film Encapsulation

Our studies indicated that the multi layers thin film encapsulation (TFE) provided good gas barrier property to the flexible OLED display. However, the barrier layer of TFE is too fragile to crack during bending process. How to design a good display structure to set the barrier layer be placed around stress neutral layer is very important. The purpose is to balance the stress caused by bending by adjusting the thickness of planarization layer and the function film thickness like cover film and polarizer film. Particle coverage ability is another evaluation item of TFE process. In figure 4, we designed a 11um height photo spacer (PS) as particle and used three layers TFE encapsulation to compensate PS particle, we made different thickness of organic layer and test the compensate ability of TFE encapsulation unit. The inorganic layer covered PS completely with 8.2um and 10um organic layer and it means the TFE structure can provide good gas barrier in the particle area. But one issue need to be studied in the future is that stress concentration on the top of 8.2um is more serious than 10um. We need to test the WVTR after 100k times bending to check the TFE reliability and get the optimal structure



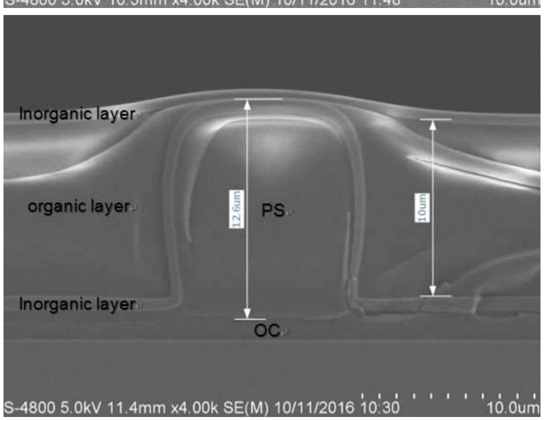


Figure 4. The cross-sectional view of PS particle which were fabricated on over coating layers (OC). 3 layers TFE deposited on it. Both 8.2um (a) and 10um (b) thickness organic layer could cover it completely.

Nowadays, slim border and even the borderless panel are becoming the mainstream. This is another challenge for OLED displays especially for the flexible display. The slimmer the border, the more challenges for the panel manufacturers. The border panel design should not only consider the encapsulation reliability of the TFE layers but also take account of the backplane design. For examples, arc-shape design in corner of TFE mask helped to decrease the stress concentration. Barrier dams were set along the edge of active-area (AA) of the display to control the planarization layer which fabricated by inkjet process .

2.4 Flexible module process

The typical bonding method has chip on plastic (COP) and chip on film (COF). The COP has some challenges due to the difference of hardness between flexible substrate and IC, IC sank into flexible substrate after main bonding process and bonding pads crack due to the pressure of bump and may cause failures in electrical connecting.[2] Use COF bonding to overcome the problem of interface hardness, but bonding alignment to be resolved for manufacturing. Inner tension will be introduced through PI coating and array process. When panel separated from carrier glass, PI substrate will shrink because of tension release. Dimension compensation should be calculated before panel bonding bad and COF are designed and this compensation should base on stable PI coating and array process in order to acquire high uniformity after lift-off process, but still will be a challenge for COF alignment especially when COF pitch getting smaller for high PPI display. Our study is 5.5 inch QHD display which COF bonding pad is 11um and space is 14um. With dimension compensation we can get good results of flexible bonding.

After panel bonding, the flexible display must be laminated with touch sensor and 3D edge cover glass or cover film. Use the vacuum lamination with jig can be effective to laminate in the bended edge area. In order to reduce delay bubbles and edge peeling or delamination after reliability test, the thinner optical clear adhesive (OCA) with high ink-step absorption will be needed.

3. Result

By overcome the challenges step by step, we succeed demo 4.35", 4.8", 5.5", 7.8" and 10.9" flexible OLED displays in recent years. The 7.8" flexible OLED display shows good flexible performance in figure 5. After 100k times bending at radius 5mm , the display can work as well as beginning and no new defect appeared.

Figure 5. 7.8" flexible OLED display with 5 mm radius bending jig

4. Conclusion

In this paper we discussed some challenges in flexible OLED display including flexible substrate preparation, lower temperature w/ LTPS (L-LTPS), thin film encapsulation and flexible module process. Of course there are many other difficulties else which were not be discussed or found in our study. It is meaningful to collect and summary the past experience to get closer and closer with matured flexible OLED display technology.

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