Improvement of Horizontal Line Defects in MicroLED Displays

Xiaoping Yu*, Baolin Chi*, Ning Zhang*, Hongyuan Xu*, Chung-Ching Hsieh*
*R&D Center, TCL China Star Optoelectronics Technology Co., Ltd., Shenzhen, Guangdong, China

Abstract
Horizontal lines were discovered during the reliability test of micro-LED display. The basic reason is the short of metal lines with different voltages owing to edge design and film structure. By optimizing process flow and backplane design, the defect is significantly improved. Furthermore, several suggestions of design have been proposed.

Author Keywords
Horizontal line defect; metal line short; edge design; film structure.

1. Introduction
In recent years, owing to the advantages such as better view angle and image quality, higher contrast ratio and brightness [1], the shipment of mini/micro-LED display with small pitch is continuously increasing, especially the display with P1.7-2.5. And the displays with ≤1.0 ultra-fine pitch are mainly used for security and control room, corporation and education, and entertainment and cinema, with high resolution demand [2]. However, the development of micro-LED display meets challenges such as driver choice, mass transfer technology, encapsulation method and inspection and repair process [3]. Owing to these challenges, mini/micro-LED display is always assembled with small panels. To improve the visual experience, the gap between the contiguous panels should be as small as possible, which brings rigorous challenge of bonding process and encapsulation technology.

To evaluate the reliability, panel makers simulate the lifetime by rigorous test conditions such as high temperature and high humidity to accelerate the aging of display. As shown in Fig.1, horizontal line defects occur during reliability tests of the micro-LED panels with ultra-fine pitch as P0.86. This paper analyzes how the horizontal line defect occurred in details and provides methods to improve the line defect through design and process optimizations.

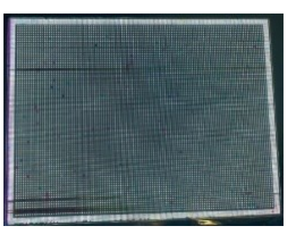

Figure 1. The horizontal line defect image

2. Phenomena and cause analysis

2.1 Analysis of the Location of Horizontal line Occurrence
In order to analyze the cause of the horizontal line defect, we use an infrared imager and laser cutting method to locate the short-circuit position. As shown in Fig.2, after the cutting process, all the pixels charging before the short position light up again, indicating that the cutting has interrupted the conductive path which caused the short circuit, thus restores the normal operation of the pixels.

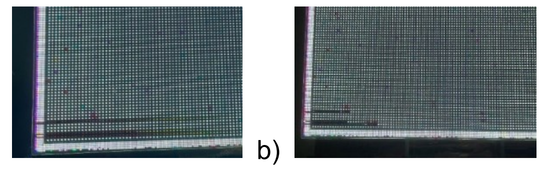

Figure 2. The horizontal line defect: a) before laser cut, b) after laser cut

Furthermore, we map the positions where the short circuits occurred and find that the short circuit locations can be divided into two types: one concentrates on the edge of the panel, and the other is inside the panel. Therefore, we speculate that the causes of the horizontal line defects can also be divided into two types.

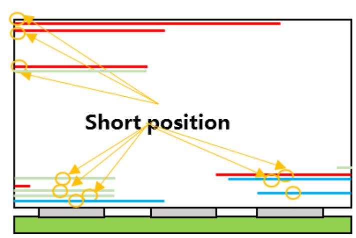

Figure 3. The mapped short positions in panels

2.2 Analysis of the horizontal line defect
For further analysis, optical microscope (OM) and scanning electron microscope (SEM) are adopted to detect the phenomenon of the short-circuits. As shown in Fig.4, the short on the edge of the panel occurs at the cross position of metal lines with different voltage, such as VSS-gate or data-gate, which is proved by SEM. This type of short is caused by water vapor corrosion, owing to the insufficient protection of the encapsulation of micro-LED panel. The actual voltage of gate is pulled down by the voltage of VSS or data, so the effective voltage of pixel is lower than expected, leading to lower brightness so much as totally darkness. Meanwhile, the short affects the next pixel charging, and finally causes horizontal gradient line defect. The other type of the short inside micro-LED panel is caused by the steep taper of metal line and the thin passivation layer between data and gate lines or gate and VSS lines. As shown in Fig.5, the passivation film is only about 2000A. If big particle is dropped during the CVD process of the passivation film, short circuit easily occurs as the electric current flows into metal lines. The effective method is to reduce the taper of metal lines and increase the thickness of passivation film.

ISSN 0097-996X/25/5602-0829-$1.00 © 2025

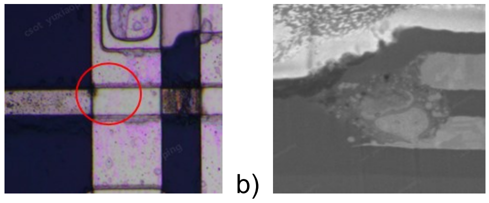

Figure 4. The image of edge short position: a) by OM, b) by SEM

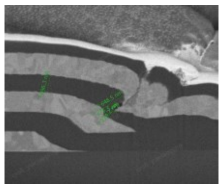

Figure 5. The SEM image of line cross position with different voltage inside the panel

3. Experiment

The processes of micro-LED panel include backplane process with a-Si or IGZO TFT, mass transfer of micro-chips, die bonding, laser cutting, bonding and encapsulation process.

To improve the horizontal line defect, we analyze the path of the water vapor corrosion. As illustrated in Fig.6a, after the laser cut process, the cell test lines extend to the edge of panel. The passivation film is damaged during laser cut process, leading to a gap between passivation film and substrate glass, so much as the passivation film probably is separated from substrate glass as Fig.6b. The passivation film separated from glass is proved to be organic PLN film by SEM as Fig.6c. Water vapors invade along the gap after passing through the outer layer of encapsulation films, and corrode the Cu lines, which leading to the short as the corrosion becomes more and more serious. The damage is caused by the thermal effect during infrared laser cut process, and we suppose that the less thermal effects the less damage. So, we try different cutting methods and the damage is barely observed by UV laser cut with much less thermal damage.

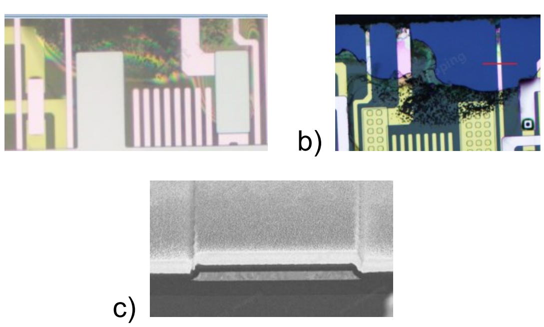

Figure 6. The image after laser cut: a) before separation, b) after separation by OM, c) by SEM

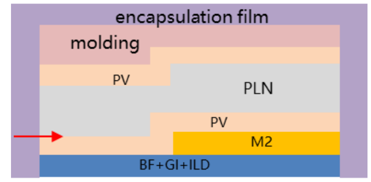

Figure 7. The diagram image of the path of water vapor

Another key factor is the distance from the cross of the metal lines to the edge of panel. Because of the insufficiency protection of the outside encapsulation films, the closer to the edge, the earlier corrosion occurred. Therefore, we can avoid the corrosion by designing the metal line cross far away from the edge of panel.

To solve the short issue inside the panel, we investigate micro-LED panels with different structure of passivation film and RA results. As shown in Table 1, panel with thicker passivation film performs better during HTHHO test. The film thickness between data and gate lines is especially important, which can be change by setting gate line in LS layer or adding PLN film under data lines (Fig.8). Different from inorganic passivation film, the thickness of organic PLN film is usually more than two micrometers, which could decrease the capacitance between data and gate lines and improve the voltage tolerance.

Table 1. panels with different passivation structures

Product	Panel 1	Panel 2	Panel 3
The thickness between of passivation film/A	a	2*a	a+2um
Horizontal line defect	T24 NG	T72 NG	T500 pass

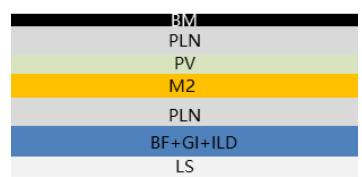

Figure 8. The film structure of metal line cross

The process in this paper is implemented in the G4.5 production line, and this paper focus on the optimization of passivation film and the laser cut process and edge design of micro-LED panels. Firstly, different films structures and thickness were studied. If we choose organic PLN as passivation film, another photo process would be added, which lead to more cost. So that we try to increase the thickness by setting the gate line at the LS layer with another 5000A inorganic passivation film. To avoid thermal damage of the passivation film, the UV laser is used with more accurate position. Meanwhile, the black film between the micro-LED chips for different colors is set to avoid the cutting line with less damage of the passivation film.

On the other way, we set longer distance from the metal cross to the edge. As we all know, the edge distance will define the gap between the contiguous two LED panels, and furtherly affect the visual experience. In this paper, we try to find the appropriate distance to the edge for design guide of micro-LED panel.

After the module process, the improved micro-LED panels are executed with HTHHO test which last for 1000Hrs with organic encapsulation film and barrier film.

4. Results and Discussion

The micro-LED panels with different improvement strategies have different performances in RA tests (table 2). The horizontal lines still occur in the panels keeping short distance to the edge by infrared laser cut method as panel 2&3, owing to the corrosion of gate-VSS metal cross by water vapor. However, the short-circuit inside the panel barely occurs. With UV laser cutting method, the damage of passivation film is improved, and the panels with thicker passivation film and longer distance from the metal cross to the edge perform better without horizontal line defect lasting for more than 500 hours, which means significant improvement compared to the reference panels. As expected, panels with further distance sustained longer time.

With the aim to avoid horizontal line defect in micro-LED display, we provide some suggestions for the design of passivation film at the edge of panel. As illustrated in Fig.9, we propose that the organic PLN film and the shielding layer between the micro-LED chips for different colors should keep away from the cut line. And it is expected that the panel with inorganic passivation film on the edge will have better performance during HTHHO test ($b \approx d > c > a$). With these design proposals, we can choose infrared laser for cut process, which could decrease the tact time of laser cut.

Table 2. RA results with different improve methods

Product	Panel 1	Panel 2	Panel 3	Panel 4	Panel 5
Distance from metal cross to edge/um	a	a	a+60	a+100	a+180
Laser cut	infrared	infrared	infrared	UV	UV
Thickness between different metal lines/A	b	b+5000 A	b+5000 A	b+5000A	b+5000A
Horizontal line defect	T24 NG	T24 NG	T240 NG	T800 pass	T1000 pass

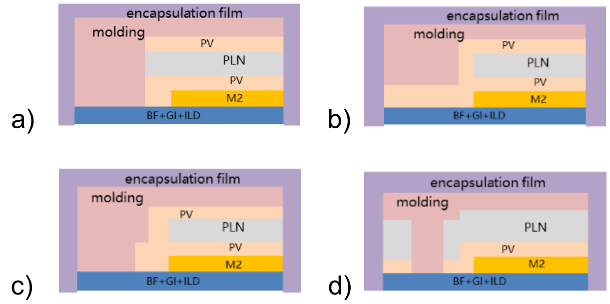

Figure 9. The diagram image of organic film design

5. Conclusion

As a common problem during the RA tests of micro-LED display, horizontal line defect is analyzed and settled in this paper. Firstly, we locate the short-circuit positions and the main factor is focused on the short of metal lines with different voltages. The root causes of horizontal line defect are the corrosion of metal line by water vapor and the poor voltage tolerance in micro-LED panel. To improve the horizontal line defect, we proposed two different strategies: optimize the process parameters to avoid the damage of passivation film and proper distance from metal cross to the edge of panel to avoid the corrosion by water vapor, and on the other hand increase the thickness between metal layers with different voltages to avoid the short-circuit inside the panels. And these methods substantially improve horizontal line defects in RA tests to T1000 passed. Furthermore, we give some suggestions for the edge design of passivation film to avoid the defect at the design moment.

6. References

[1] Z. Liu, C.-H. Lin, B.-R. Hyun, C.-W. Sher, Z. Lv, B. Luo, F. Jiang, T. Wu, C.-H. Ho, H.-C. Kuo, J.-H. He, Light: Sci. Appl. 2020, 9, 83.

[2] A. R. Anwar, S. P. Lepkowski, M.T. Sajjad, M.A. Johar, etc., “Recent Progress in Micro-LED-Based Display Technologies”, Laser Photonics Rev. 2022, 16, 2100427.

[3] K. Ding, V. Avrutin, N. Izyumskaya, Ü. Özgür, H. Morkoç, Appl. Sci. 2019, 9, 1206.