The Causes and Improvement of Lens Damage in Micro-OLED Display

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Abstract

In order to improve the light output efficiency of the device in Micro-OLED, micro-lens (Lens) are usually configured on the pixels. This paper investigates the lens damage in Micro-OLED 4k product. We found that the cause of lens damage was insufficient evaporation of the photoresist (RP) solvent due to the low baking temperature of the Bonding Pad Open (PDO) mask, which resulted in pit-like defects after development and lens damage during PDO etching. Ultimately, by removing the Post-Exposure Baking(PEB) process, we reduced Lens damage to 0%.

Author Keywords

Micro OLED; PDO; Lens Damage; white spot; Baking

1. Introduction

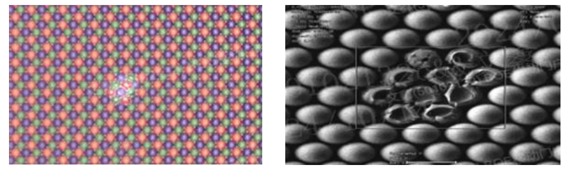
Silicon-based organic light-emitting micro-display panels (Micro-OLED), which feature small pixel size, high brightness and high pixel density, have extensive applications in military display products, Augmented Reality (AR) and Virtual Reality (VR) technologies, as well as in the field of autonomous driving [1]. Within this technology, lens technology is a technique that significantly boosts optical efficiency by approximately 200% by focusing the light emitted by OLED devices at front view [2]. Furthermore, in applications where high brightness is not required, this technology will help reduce power consumption and extend the service lifetime [3]. However, there are some yield loss issues in this process, such as display defects called white spots which are caused by lens damage.

This study investigated the issue of lens damage in silicon-based Micro-OLED 4K product which resulting in a significant yield loss of approximately 20%. Our verification reveals that the PR utilized in the PDO mask process is thick, yet the baking temperature is limited to below T1 ℃ (exceeding T1 ℃ OLED device would be damaged), resulting in insufficient volatilization of the PR solvent. This leads to the formation of pit-like defects after development (PR thinned ~30%), where the lens will be damaged during the subsequent PDO etch process. Based on the mechanism analysis, process adjustments were implemented to weaken or improve the occurrence of defects when increasing the baking temperature was deemed impractical. Ultimately skip PEB effectively reduces the defect to 0%.

2. Research and Discussion

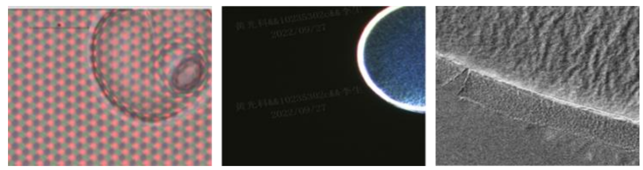
2.1 Phenomena

The initial identification of lens damage occurs after PDO etch process, identified by Automated Optical Inspection (AOI) equipment as irregular white morphologies, as shown in Figure 1(a). Scanning Electron Microscope (SEM) shows that the upper part of lens is damaged, as shown in Figure 1(b). Tracing back the lens damage, the earliest identifiable match is associated with bubble-like defects detected by AOI after PDO mask process, as shown in Figure 2(a). A detailed analysis of the anomalous region using both Optical Microscopy (OM) and SEM reveals that PR within this specific area exhibits a characteristic pit-like morphology, as shown in Figure 2(b&c). Furthermore, Atomic Force Microscopy (AFM) measurements indicate a significant 30% reduction of PR thickness, as shown in Figure 3.



(a) AOI Image (b) SEM Image

Figure 1. The Image of Lens Damage



(a) AOI Image (b) OM Image (c) SEM Image

Figure 2. The Image of Lens Damage Matching after PDO Mask Process

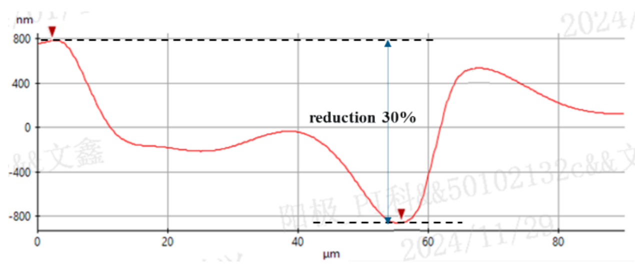


Figure 3. AFM Measurement of the Anomalous Region

During Final Test, the defects are identified as white spots which are attributed to the Chief Ray Angle (CRA) process applied to this 4K product to improve luminance uniformity. Both AOI and Final Test inspections are conducted at an angle of 0°, as shown in Figure 4. Optical simulation results indicate that when the lens is damaged, the luminance without focusing aligns with that observed in the absence of a lens (represented by the orange curve in Figure 4). Conversely, in normal areas (represented by the black curve in Figure 4), due to the customized inspection angle of 0°, the actual luminance is diminished compared to that without a lens, causing the damaged portions of the lens to appear notably white.

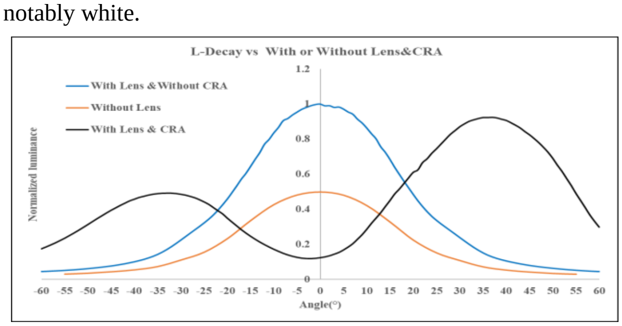


Figure 4. Optical simulation diagram of L-Decay

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2.2 Mechanism analysis

The PDO process is specifically engineered to expose the Pad through the use of a mask and etching techniques. This preparation allows for the subsequent Bonding process, where the exposed Pad can be connected to both the Integrated Circuit (IC) and the Flexible Printed Circuit (FPC). This connection establishes the necessary electrical pathway to the exterior, as shown in Figure 3.

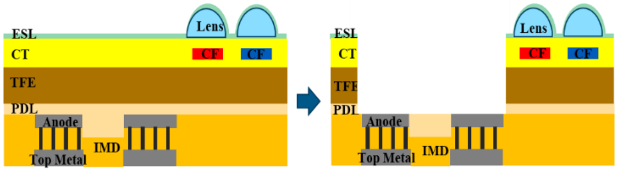


Figure 5. Structure diagram before and after PDO process

After conducting a thorough investigation, we discovered that the root cause of the pit-like defects observed in the PDO Mask stems from the combination of a thick PDO Mask PR and a relatively low baking temperature. This condition leads to inadequate evaporation of the PR solvent, resulting in the formation of bubbles that eventually evolve into pit-like defects after development. Notably, the manufacturer of the PR recommends a baking temperature range of T1+20 ℃ to T1+30 ℃ for optimal performance. However, considering the impact of temperature on OLED device performance, the heating process must be restricted to a maximum of T1 ℃.

Within the PDO mask process, we identified three distinct heating steps, as highlighted in Figure 6 (blue frame). Each of these steps is conducted at T1 ℃. In order to pinpoint the specific baking step that contributes to the pit-like defects, we conducted a series of experiments, as shown in Table 1. In experiment 1, no corresponding defects were observed, as shown in Figure 7(a). Conversely, in experiment 2, bubbles were detected, which are hypothesized to be the precursor to pit-like defects, as shown in Figure 7(b). Based on the experimental results, we conclud that the PEB step is the earliest heating process where defects first appear.

PR is an organic material susceptible to reaction with the process gases used during the PDO etch, consequently resulting in a reduction of the PR thickness. To quantify the actual PR loss incurred during PDO etching, an experiment was devised where a dummy wafer was coated with a PR layer of thickness1 um. Subsequently, the PDO etch process was performed on this coated wafer. The difference in PR thickness measured before and after the etch process represents the PR loss attributed to the PDO etch, which was found to be approximately 50% reduced. This 50% of thickness1 um is considered the minimum safe threshold for PR during PDO etching to ensure process integrity.

In conclusion， the inadequate temperature during the Soft Bake (SB) process of the PDO Mask results in incomplete volatilization of the PR solvent. During the PEB process, as the solvent undergoes further volatilization, the surface of the PR becomes hardened, impeding the subsequent volatilization of residual solvents and leading to the accumulation of bubbles on the PR surface, as shown in Figure 8(a). During the development process, while the developer effectively removes the PR in the exposed area, it also softens the hardened PR surface resulting from the PEB process. Concurrently, the regions with bubble defects react with the developer, leading to the formation of pit-like defects. This results in the actual thickness of the PR in these areas being reduced to only 35% of thickness1 μm, which is below the minimum safe thickness of 50% of thickness1 required for PDO etch, as shown in Figure 8(b). Consequently, during the PDO etch process, the lens located within these pits undergo partial etching, causing significant damage, as shown in Figure 8(c).

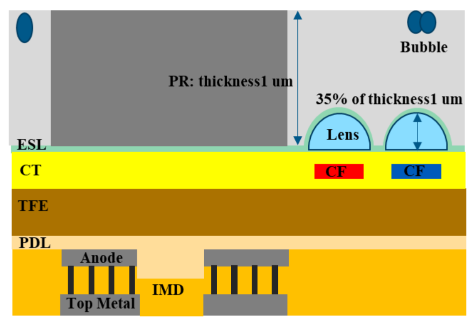
Figure 6. Three Heating Steps in the PDO Mask Process

Table 1. Experiments about PDO Mask Baking Process that Contributes to the Pit-like Defects

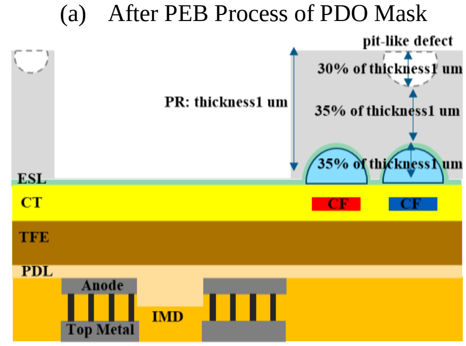
Item	Detail	Result	Image
Experiment 1	COT→ SB→AOI	OK	Figure 7(a)
Experiment 2	COT→ SB→EXPO →PEB→AOI	NG	Figure 7(b)
Base	COT→SB→EXPO→ PEB→DEV→HB→AOI	NG	Figure 7(c)

(a) (b) (c)

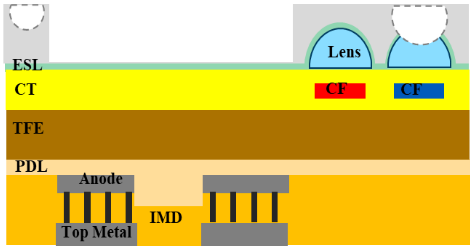
Figure 7. The Image of Experiment Results



(a) After PEB Process of PDO Mask



(b) After Development of PDO Mask



(c) After PDO Etch

Figure 8. Mechanism of Lens Damage

3. Verification and Improvement

The lens damage observed in 4K products is attributed to the thinning of the PR to approximately 30% of thickness1 at the pit-like defect areas of the PDO mask. This results in the actual thickness of the PR falling below the minimum safe thickness of 50% of thickness1 required for PDO etch. In the absence of adequate PR protection, the PDO etch process causes damage to the lens. Based on a comprehensive analysis of these underlying causes, improvements will be implemented in two key areas: process optimization and root cause improvement.

3.1 Optimization

Based on the observation that the PR protection area is thinner than what is required to withstand the material loss during PDO etching, process optimization can be achieved by increasing the PR thickness on the PDO mask and minimizing the PR loss during the etching process.

We conducted verifications by increasing the PR thickness on the PDO mask, specifically to 115%, 130% and 150% of the initial thickness1. As shown in Figure 9, the incidence of lens damage decreased but was not completely eliminated.

Additionally, we reduced the over-etching time of PDO Etch. However, Energy Dispersive X-ray (EDX) test results revealed the presence of SiO_x residue in the Pad area, resulting in a high impedance. This optimization measure is ineffective.

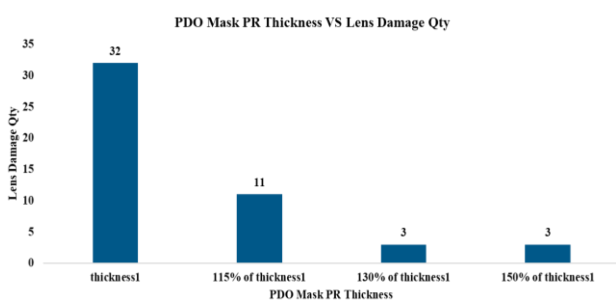


Figure 9. The Relationship between PDO Mask PR Thickness and Lens Damage

3.2 Root cause improvement.

The root cause of lens damage has been traced to pit-like defects in the PDO mask. It was identified that the PEB step is where these defects first emerge. However, directly increasing the PEB temperature is not feasible due to the potential adverse impact on the performance of OLED devices if it exceeds T1℃. Consequently, two approaches for improving the PEB process were explored:

Firstly，we extended the PEB time from the baseline to 200% and 300% of the baseline. The AOI test still revealed the presence of bubble defects, indicating that the measurement was ineffective.

Secondly, skip the PEB directly, the AOI test showed no bubble defects, and subsequent re-tests also confirmed the absence of bubble defects. We speculate that skipping the PEB step prevents the solvent from re-volatilizing, thereby eliminating the adverse accumulation of bubbles on the surface and preventing the formation of pit-like defects. This modification achieved a significant improvement. We introduce the PEB Skip into the PDO mask of 4K production. There is no lens damage in the AOI monitoring.

4. Conclusions

In this paper, we investigate the issue of lens damage in silicon-based 4K products. The research shows that: due to the baking temperature of PDO mask is limited to below T1℃, the evaporation of PR is insufficient. Pit-like defects emerge after development where cause lens damage during the PDO etching. Increasing the PR thickness of the PDO mask can decrease the ratio of lens damage, but cannot completely eliminate it. Ultimately, skip the PEB process reduces the defects to 0%.

5. References

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