

A Prediction Model of Pixel Shrinkage Failure Using Multi-physics in OLED Manufacturing Process

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Abstract. Recently, as the application range of high-end Organic Light Emitting Diodes (OLED) displays has expanded, the pixel area has become larger and panel architecture complexity has been raised to increase the lifespan and efficiency of the panel. At the same time, the remaining moisture in the organic material of the panel increases, and pixel shrinkage defects in which the pixel edge emission area is reduced by cathode oxidation due to moisture diffusion within the panel are increasing. Therefore time and cost are incurred in the process of design and manufacturing process enhancing to improve reliability of the display panel. In this study, we introduce an analysis model that can quantify pixel shrinkage and predict the occurrence of defects in advance. In order to make up for the shortcomings of existing Finite Element Method (FEM) and numerical analysis models, product design specifications were applied through layout-based 3D geometry, and the degree of curing according to the heat treatment conditions of organic materials was calculated and the physics of moisture diffusion between subsequent cleaning and oven process were also applied in the model. The degree of moisture absorption during the waiting time between processes, one of the main factors affecting defects was applied in connection with the curing rate of organic materials. In addition, the residual concentration after moisture diffusion in the final deposition process was quantified and matched with the actual shrinkage defect occurrence level to optimize design and process factors of the model. As a result of verification based on 20 evaluation models, the consistency of about 0.96 based on R2 was confirmed.

Keywords: OLED · Pixel Shrinkage · Remaining Moisture · Diffusion

1 Introduction

Recently, demand for OLED continues to grow rapidly in a wide range of areas from high-end smartphones to IT products such as laptops and tablet PCs as well as automobile and TV. In particular, OLED panel shipments for IT products were reached 15 million units in 2022. This is almost double as many as the previous year [1].

As the utilization of OLED increases in various devices, a high pixel area ratio is required to increase the lifespan of the panel, and the complexity of panel architecture is also increasing as high efficiency and new form factor technologies such as Under

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Panel Camera (UPC) is applied. As a result, the residual moisture in the organic layers between processes increases due to the high-density metal wiring and pixel area. And it causes Pixel Shrinkage (P-SK) defects in which the light emitting area is reduced due to cathode oxidation, as shown in Fig. 2, and this leads to affect production yield and reliability [2].

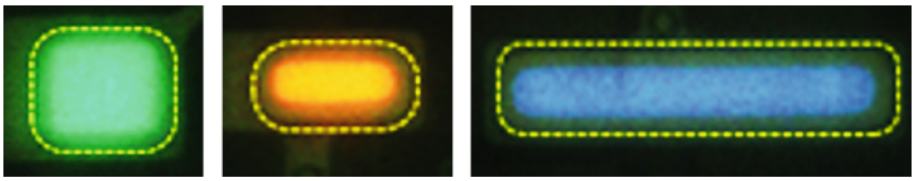

Fig. 1. Pixel Shrinkage defective image.

In addition to various efforts from design and process perspectives such as design revision and organic layer heat treatment reinforcement, numerical analysis model development activities are also being carried out for prediction of defects in advance. For example, as shown in Fig. 2, an analysis model and an index were developed to predict the residual moisture in the organic material according to the design specifications through the FEM model. Since process factors were not applied, the influence of process conditions cannot be predicted, so it can be used only for design verification.

In addition, another prediction model was developed through a mathematical model using both design and process factors, such as Eq. (1). It contains weights for design factors and organic layer heat treatment process factor. However, the omission of the panel structure and the waiting time between processes called Cooling Buffer (C/B), which are highly correlated with the occurrence of P-SK are not applied.

$$Index\#2 = pixel\ Area \times Organic\ Thickness \times \sqrt{\frac{PXL\ Ratio}{Organic\ Open\ Ratio}} \times Process\ Index \tag{1}$$

In this study, we would like to introduce the methodology and model for improving the previously developed P-SK prediction model. Moisture emission characteristics according to the design specifications were applied through panel architecture modeling. And the residual moisture concentration according to the moisture diffusion between processes was calculated by deriving the diffusion rate for each process condition through the Water Vapor Transmission Ratio (WVTR) characteristics of organic materials and the Arrhenius Equation. The curing rate of the materials between the organic layers heat treatment processes was calculated and applied to the moisture absorptivity in C/B process to derive the P-SK Index applying the design and process factors.

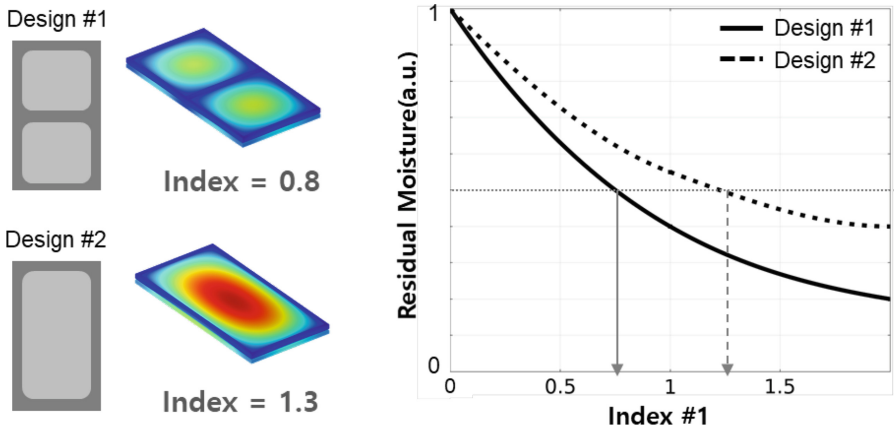

Fig. 2. Previously Developed Pixel Shrinkage Defect Prediction Model (Index #1)

2 Development of P-SK Quantification Analysis Model

2.1 Defect Mechanism

The main causes of pixel shrinkage defects have been identified through material analysis and various simulation evaluations. In the Backplane (BP) process, the organic layers go through processes such as coating, exposure, and development, and then material hardening and moisture emission are performed through a heat treatment process. In this process, as shown in Fig. 3(a), the metal wiring and the pixel layer which have a very slow diffusion rate compared to organic materials are arranged in a complex manner between the organic layers, serving as obstacles to block the path for moisture diffusion. After the heat treatment process, the remaining moisture in the organic layers which oxidizes the cathode layer by diffusion after encapsulation causes shrinkage defects in the pixel light emitting area.

2.2 Process Factor of P-SK

In addition to the design factors mentioned above, P-SK defects are affected by various process factors such as heat treatment of organic layers, cleaning, oven, and C/B time. First, in the heat treatment process, it is affected by the heating profile of the chamber and the duration of the process. The higher the temperature and the longer the time, the faster the diffusion rate and release of moisture, and the amount of moisture remaining in the organic film is reduced. Through this, by increasing the curing rate of the organic layers, it is possible to see the effect of reducing the amount of re-absorption of moisture in a subsequent moisture absorption-induced process such as C/B.

At the P-SK generation level according to the organic layer heat treatment conditions in Table 1, Treatment2 which is a relatively strong heat treatment condition compared to Treatment1, 270 °C/1 h was applied to different organic layers and the effect was compared. As a result of the evaluation, the largest amount of shrinkage was occurred in the condition consisting of only the Treatment1(#1), and a relatively low amount of

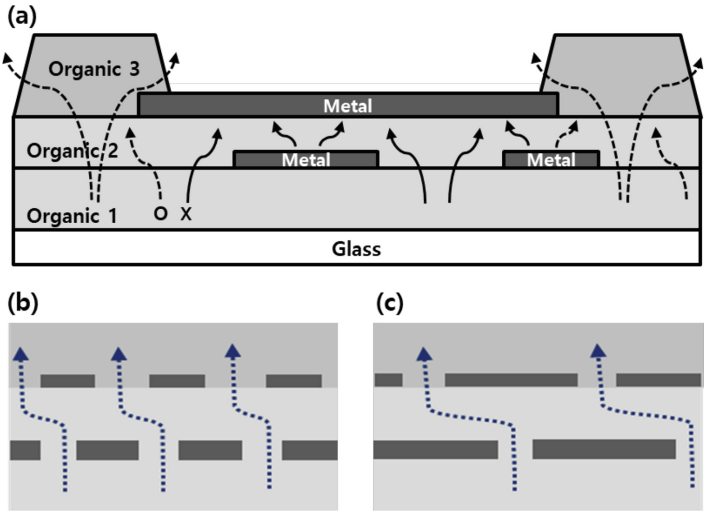

Fig. 3. (a) Mechanism of Pixel Shrinkage (P-SK). (b) P-SK non-occurring structure. (c) P-SK occurring structure

shrinkage occurred in the evaluation of #2 to #4 including the Treatment2, which is a strong heat treatment condition compared to Treatment1. According to this result, it can be seen that the effect is greatest when the application sequence of the strong heat Treatment2 process is applied to the last organic layer.

Table 1. Organic layer heat treatment process reinforcement evaluation result (Treatment1: 270 °C/1 h/Heating Profile1, treatment2: 270°C/2 h/Heating Profile2)

Condition	Heat Treatment			P-SK(um)
	Organic1	Organic2	Organic3	
#1	Treatment1	Treatment1	Treatment1	1.5
#2	Treatment2	Treatment1	Treatment1	1.2
#3	Treatment1	Treatment2	Treatment1	1.4
#4	Treatment1	Treatment1	Treatment2	0.8

Through the results in Table 2, the correlation between C/B time and P-SK occurrence level can be confirmed. The split evaluation was conducted with the Treatment2 heat treatment conditions relatively weaker than the Treatment1, 250 °C/2 h and 270 °C/1 h respectively. As a result, despite the application of different heat treatment processes for each organic layer, no defects occurred in all conditions when C/B time was less than 0.1. But when C/B time increased to 0.3 or more, evaluation except for the strongest heat treatment condition (#1) shrinkage defects occurred in all of them, and it can be seen that the evaluation (#5) where Treatment2 is applied to the last organic layer is the most

vulnerable condition. From this, it can be seen that C/B time is also closely related to the occurrence of shrinkage defects, and the difference in residual moisture and curing rate according to heat treatment conditions affects moisture absorption during C/B, resulting in different levels of shrinkage can be expected even at the same C/B time.

Table 2. P-SK occurrence level according to heat treatment conditions and C/B time (treatment1: 270 °C/1 h/Heating Profile1, treatment2: 250 °C/2 h/Heating Profile2)

Condition	Heat treatment				P-SK(um)	
	Organic1	Organic2	Organic3	Organic4	C/B Time	
					<0.1	>0.3
#1	Treatment1	Treatment1	Treatment1	Treatment1	0	0
#2	Treatment2	Treatment1	Treatment1	Treatment1		1.0
#3	Treatment1	Treatment2	Treatment1	Treatment1		1.2
#4	Treatment1	Treatment1	Treatment2	Treatment1		1.0
#5	Treatment1	Treatment1	Treatment1	Treatment2		1.4

2.3 Method

We built a multi-physics analysis model based on COMSOL S/W that can quantify shrinkage by applying the design factors identified above, curing of organic materials, and major process factors such as C/B time. As shown in Fig. 4, the entire analysis process proceeds in 5 steps, and consists of design layout-based geometry generation, hardening for each organic material, cleaning/oven, moisture absorption during C/B and moisture diffusion.

First, the 3D structural domain is completed by applying the design layout and the thickness of each material using software. Through this work, it is possible to improve the disadvantages of the existing design rule-based P-SK prediction model, such as Eq. (1) (Fig. 4).

Second, the curing rate according to the heat treatment process conditions for each organic layer is calculated. As shown in Fig. 5(a), through the curing rate evaluation data of organic materials, it can be seen that the curing rate of the material is highly sensitive to temperature increases (250 °C to 270 °C) compared to the increase in process time (60 min to 120 min).

Based on this, an analysis model that can calculate the curing rate of the material according to the process temperature and time was established using the two functions in Fig. 5(b) and (c).

After the heat treatment process, the inflow and diffusion of moisture generated during the cleaning and oven processes were implemented. In the analysis model, the inflow of water between washings was reflected as the initial water concentration in each organic layer domain using the analysis boundary condition. After that, in the oven

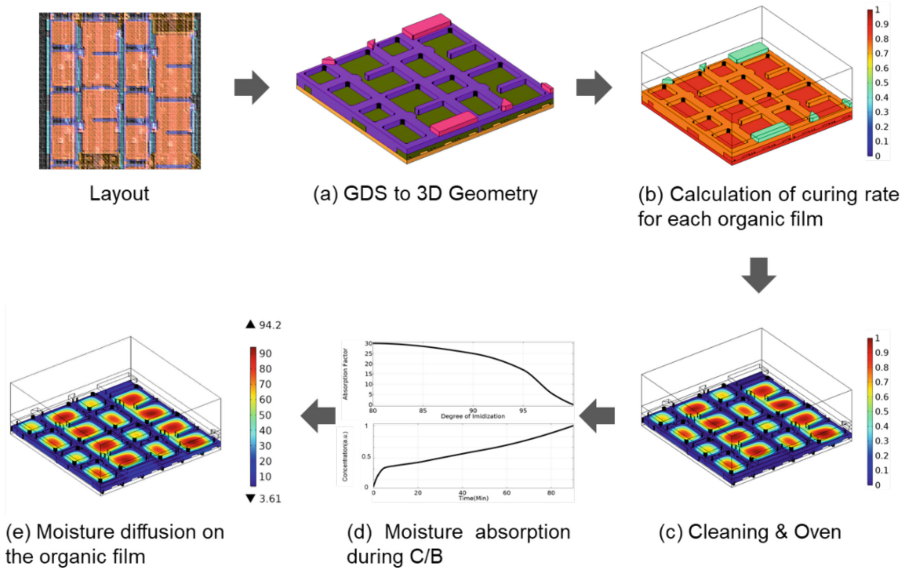

Fig. 4. P-SK Quantification Analysis Model Workflow

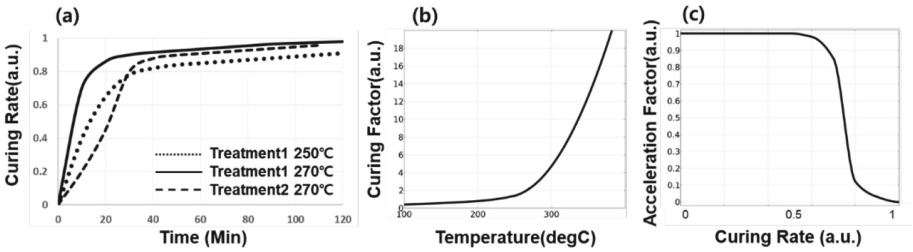

Fig. 5. (a) Curing rate analysis result for each process condition using evaluation data, (b) Material curing factor function according to process temperature, (c) Curing progress speed function according to curing rate

process, drying is performed for about several minutes at high temperature conditions. The analytical model for this process was implemented through Fick's 2nd Law Eq. (2) and the temperature-dependent diffusion Eq. (3) in the form of the Arrhenius Equation.

$$\frac{\partial C_i}{\partial t} = \nabla \cdot (D_i \nabla C_i) \tag{2}$$

$$D = D_0 \cdot exp\left(\frac{E_A}{RT}\right)_i \tag{3}$$

where C_i are the concentrations of organic layers, D_i are diffusion coefficient of each layer, D_0 is pre-exponential constant, E_A is activation energy for diffusion, $\mathrm{R} = 8.31(\mathrm{J/mol} - \mathrm{K})$ is the gas constant, and T is temperature in Kelvin. As a result

of the analysis, it can be seen that the residual moisture concentration at the bottom of the pixel electrode is high through the residual moisture concentration distribution in Fig. 6(a), and the change in the residual moisture concentration in the organic layers during the process time is confirmed as shown in (b). This pattern of change can appear differently through design factors such as pixel design and organic material thickness, oven temperature difference through the above Eq. (2) and (3), and increase or decrease of process time.

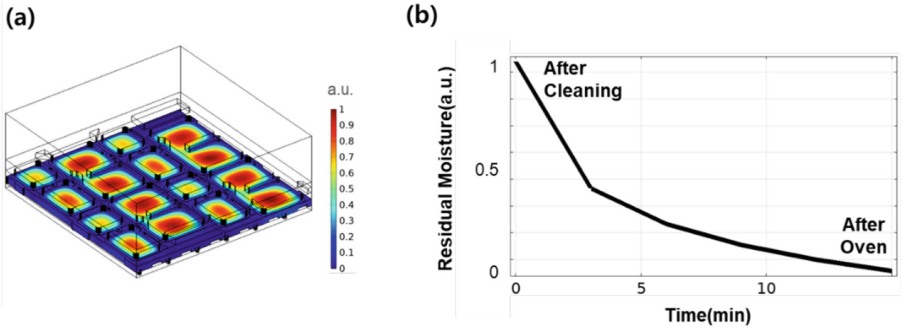

Fig. 6. (a) Distribution of residual moisture concentration in organic layers after Oven process. (b) Residual moisture concentration-time analysis result between cleaning and oven process.

Finally, the P-SK quantification analysis process which indexes the final amount of remaining moisture in the organic layers is completed based on the water inflow during C/B and the diffusion model to the outside air during the deposition process. After drying in the oven, the panel increases the moisture in the organic layers by the inflow of outside air during the waiting time at room temperature. In the analysis model, the process influence was applied by increasing the moisture in the organic layers of the analysis domain through the combination of the two functions in Fig. 7(a) and (b). As shown in the evaluation data previously introduced in Table 1 and 2, a difference in curing rate occurs depending on the heat treatment process conditions of organic layers, and the final curing rate affects the amount of moisture absorption during C/B.

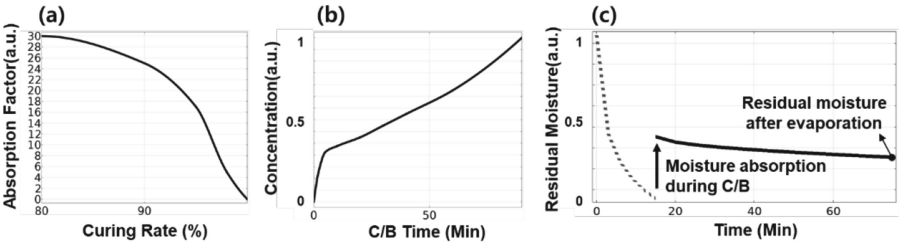

Fig. 7. Function to quantify organic material water inflow during C/B. (a) Moisture absorption – Curing rate. (b) Moisture concentration – C/B time (c) moisture content in organic materials between processes

Table 3. P-SK occurrence level according to heat treatment conditions and C/B time (treatment1: 270 °C/1 h/Heating Profile1, treatment2: 250 °C/45 min/Heating Profile2, treatment3: 270 °C/1 h/Heating Profile2, treatment4: 270 °C/2 h/Heating Profile1)

Model	Heat Treatment				P-SK (um)		
	Organic1	Organic2	Organic3	Organic4	C/B	Measurement	Sim.
#1	Treatment1	Treatment1	Treatment2	-	1.0	0	0
					2.0	0	0
					4.0	2.50	2.79
					6.0	4.50	4.53
#2					1.0	1.80	1.97
#3						0	0
#4						0.40	0
#5						2.00	2.55
#6						1.50	2.06
			Treatment1			0	0
			Treatment3			0.50	0
#7	Treatment1				0.3	0	0
					0.4	0	0
					0.6	1.58	2.30
					0.9	3.40	4.45
	Treatment1		Treatment4		0.3	0	0
					0.4	0.53	0.61
	Treatment4				0.5	1.78	1.78
					0.9	3.03	4.14
					0.4	0	0

This phenomenon was applied as a characteristic to the higher moisture absorption coefficient as the curing rate decreases, as shown in Fig. 7(a). And the amount of moisture absorption over time (mol/m^3) shows an increase in linear type after a rapid increase in the initial C/B time. These two functions were calibrated based on the heat treatment evaluation in Table 2 and the amount of P-SK occurred according to C/B time in #1 of Table 3. The amount of moisture absorbed during C/B through the multiplication of the two functions is added to the amount of residual moisture in the existing organic domains. The amount of moisture in the organic layers before the deposition process is defined in this way.

The final deposition process and P-SK quantification are completed through the moisture diffusion analysis to the outside air. Diffusion analysis proceeds through Fick's 2nd Law Diffusion Equation of Eq. (2) based on the diffusion coefficient calculated through Eq. (3) in the same way as the existing Oven process. After completion of the

analysis, the residual moisture concentration (mol/m^3) in the organic layers was indexed in units similar to the amount of P-SK generation (um) through post-processing.

2.4 Verification

To verify consistency, evaluation data for a total of 20 cases including models and process splits were obtained as shown in Table 3. The data is the result of measuring the degree of shrinkage of actual pixels after applying the heat treatment process and C/B time for each organic layer differently to evaluate the process impact.

As a result of analyzing and calculating the index using the P-SK analysis model introduced earlier, the consistency between the actual measurement and the index was confirmed to be about 0.98 based on R2 as shown in Fig. 8. In the future, the task of function calibration, which is applied to additional consistency verification and analysis through the expansion of evaluation models with accurate process conditions remains, and verification and evaluation will be conducted through model data to be developed later.

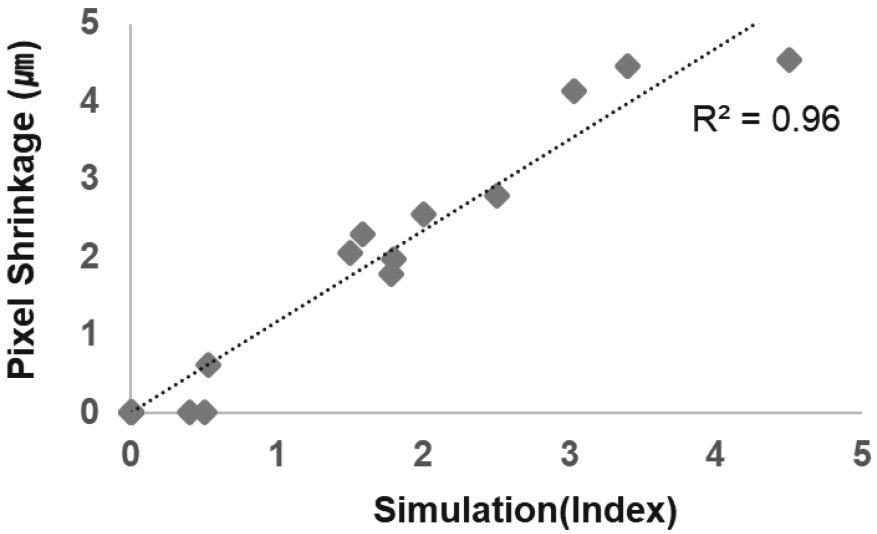

Fig. 8. Pixel Shrinkage Measurement - Index Consistency

3 Conclusions

In this study, we proposed an analysis model that can predict pixel shrinkage caused by the residual moisture in the organic layers according to the increase of pixel area and panel architecture complexity.

In order to improve the disadvantages of the previously developed FEM and numerical analysis models, design elements were applied through the creation of design layout-based 3D geometry. And the influence of process factors using evaluation data was reviewed and related physics were applied to the model.

As a result, the consistency based on 20 evaluation data was confirmed to be about 0.96 based on R2. Using this analysis model, it is possible to quickly predict the probability of defects and define optimal process conditions such as organic layers heat treatment conditions and C/B time in advance. It is judged that by establishing a process window for the P-SK of the model, it will be able to contribute to saving time and cost when developing a new model.

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