

Research on Improving Thin-Film Pixel Uniformity for 300ppi Pixels Using Inkjet Printing Process

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Abstract

This study explores inkjet printing for uniform thin-film fabrication in 300 PPI-class displays. By optimizing drying conditions such as natural and vacuum drying, the material flow within pixels was controlled, minimizing defects like coffee-ring effects. The results demonstrate improved pixel uniformity, highlighting inkjet printing's potential for high-resolution display manufacturing.

Author Keywords

Inkjet printing process (IJP); 300 PPI Display; Thin film Uniformity; Dry conditions; Pixel patterning.

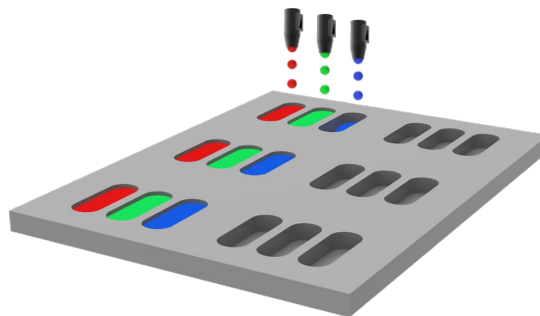


Figure 1. Schematic of Inkjet printing Process

1. Introduction

Inkjet printing has emerged as an innovative and efficient technology for advanced manufacturing, offering precise patterning, material efficiency, and cost-effectiveness. Its ability to accurately deposit functional materials has made it a promising approach in applications such as displays, sensors, photovoltaic devices, and bioelectronics. Among these, high-resolution displays demand uniform and defect-free thin films, critical for achieving superior visual performance in devices like smartphones, tablets, and VR systems.

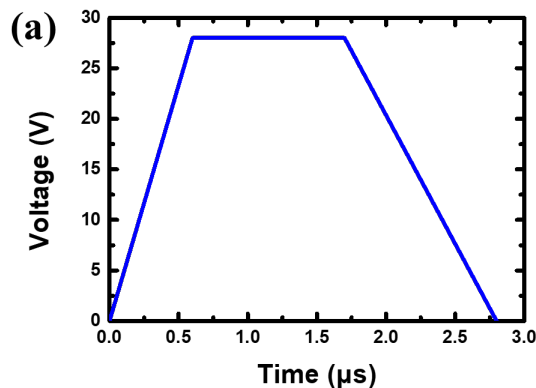
A key challenge in high-resolution display fabrication is ensuring thin film uniformity, which significantly impacts pixel performance, including color accuracy, brightness consistency, and device reliability. For 300 PPI-class displays, minor variations in film thickness or material distribution can cause noticeable defects and degrade overall performance. Addressing these challenges requires process optimization to control material flow and drying behavior during deposition.[1]

This study explores the impact of drying conditions on thin-film uniformity in inkjet-printed pixels. By introducing variables such as natural drying and vacuum drying, the research investigates how these conditions influence material flow within pixels and reduce defects such as coffee-ring effects[1]. Controlling these factors enables the formation of uniform thin films with improved consistency and quality.

Additionally, the study examines the interaction of drying parameters with other critical process factors, such as ink composition, substrate surface properties, and droplet ejection dynamics. Techniques like surface patterning and controlled droplet placement are incorporated to further enhance uniformity and edge definition.[2] These optimizations not only improve the precision of material deposition but also reduce the occurrence of defects, ensuring high-quality pixel fabrication.[3] The findings validate the potential of inkjet printing as a scalable method for producing uniform thin films for 300 PPI-class displays. This research contributes to the growing body of knowledge on inkjet printing technology and demonstrates its feasibility for next-generation display manufacturing. Furthermore, the insights gained from this work can be extended to other applications, such as sensors and optoelectronic devices, where precision and uniformity are crucial. By addressing drying conditions and process parameters systematically, this study lays the groundwork for achieving reliable and high-performance inkjet-printed electronics.

2. Results and Discussion

In this study, the light-emitting layer used in displays was fabricated using an inkjet printing process. This light-emitting layer plays a crucial role by emitting light through the recombination of electron-hole pairs delivered from the hole transport layer (HTL) and the electron transport layer (ETL). The uniformity of thin films within pixels directly impacts display device performance, including brightness, color consistency, and efficiency. Thus, achieving uniform thin films is a key factor in realizing high-performance displays. To investigate the impact of inkjet printing and drying conditions on thin-film uniformity for 300 PPI-class pixel fabrication, ethyl 4-methylbenzoate (EMB) and 2-ethylhexyl benzoate (EHB) were used as solvents for the inkjet printing process. The selection of solvents was carefully considered, with a high boiling point being a critical factor. High-boiling-point solvents help regulate the evaporation rate, ensuring that ink droplets remain stable on the substrate for sufficient time to spread uniformly. This controlled evaporation is essential for achieving consistent and uniform thin films, particularly in high-resolution displays, where precision and uniformity are critical requirements. The findings highlight that selecting appropriate solvents and optimizing drying conditions are fundamental to achieving uniform and reliable thin-film layers, paving the way for advancements in high-resolution display technologies. [4-5]



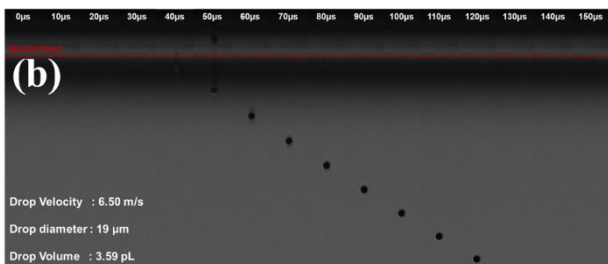


Figure 2. (a) Inkjet ejection waveform for OLED emissive layer materials based on EHB:EMB solvent. (b) Solvent ejection and droplet characteristics corresponding to the waveform.

Figure 2. shows the voltage waveform and solvent ejection behavior monitored using a drop watcher, designed to ensure ejection stability during the inkjet printing process. (a) The voltage waveform applied during the inkjet ejection process for OLED emissive layer materials using an EHB:EMB solvent base is shown. The waveform consists of a rapid voltage rise, a plateau phase, and a sharp decline, providing precise control over droplet formation and ejection. This optimized waveform stabilizes the droplet generation process and minimizes residual vibrations, ensuring uniform thin-film deposition crucial for high-resolution OLED displays.[6] (b) The solvent ejection behavior corresponding to the waveform is visualized. The sequential images capture the droplet trajectory over time, highlighting controlled and uniform droplet formation.[7] Key ejection characteristics include a velocity of 6.50 m/s, a droplet diameter of 19 μm, and a droplet volume of 3.59 pL. The consistent size and spacing of the droplets demonstrate stable ejection dynamics, verified using the drop watcher system.[4] Figure 2 confirms that an optimized voltage waveform and high-boiling-point solvents such as EHB and EMB are essential for achieving stable droplet ejection and uniform thin-film formation, critical for high-performance OLED displays.

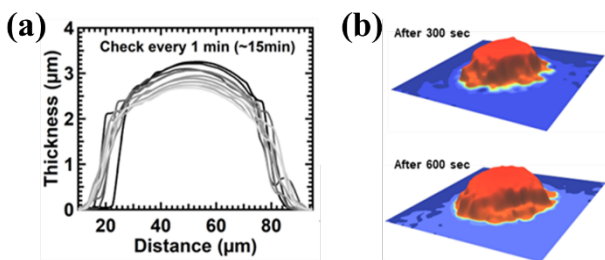


Figure 3. (a) Time-dependent changes in the droplet profile. (b) 3D images of the droplet at 300 and 600 seconds.

Figure 3 shows the droplet profile (a) and its stability over time (b) during the inkjet printing process. This evaluation is critical to ensure that the droplet remains stable and retains its shape over time, which is essential for achieving uniform thin-film formation. (a) The graph shows the thickness profile of the droplet measured at 1-minute intervals over approximately 15 minutes. The overlapping profiles indicate that the droplet's height and spread remain nearly unchanged over time. This demonstrates that the interplay between surface tension and viscosity maintains the droplet's stability after deposition. (b) The 3D images show the droplet shape at 300 seconds and 600 seconds, respectively. A comparison of these images reveals that the overall structure,

height, and spread of the droplet remain consistent, indicating minimal deformation. This stability is attributed to controlled solvent evaporation and uniform material distribution within the droplet. Therefore, Figure 3 confirms that droplets formed during the inkjet printing process maintain their stability over time, which is crucial for uniform thin-film deposition and high-quality display fabrication. Notably, the solvents used in this study, EMB and EHB, played a significant role in ensuring droplet stability. The high boiling points of these solvents regulate the evaporation rate, allowing the droplet to spread and stabilize on the substrate before significant evaporation occurs.[6] This ensures enhanced uniformity in thin-film formation. The selection of such high-boiling-point solvents is a key factor for the successful implementation of the inkjet printing process, especially for high-resolution display applications.[8]

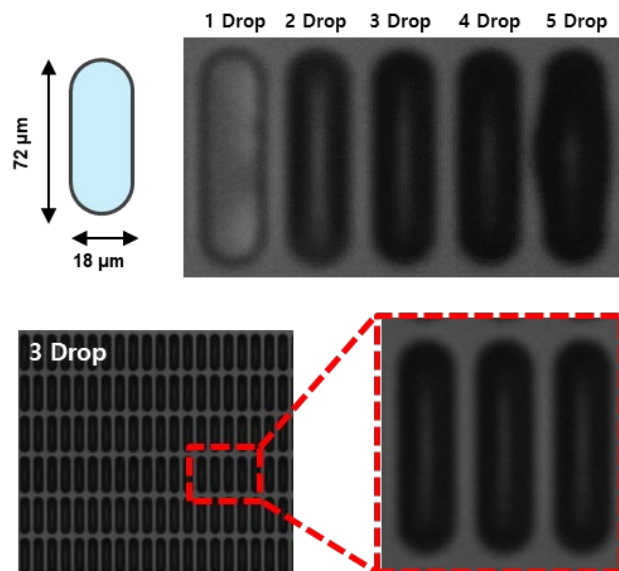


Figure 4. Optical microscopic images of inkjet-printed patterns at 300 PPI pixel and Inkjet printing at 300 PPI pixel resolution under 3-drop conditions.

Figure 4 shows the arrangement of solvent droplets and the pattern formation within the pixels at 300 PPI resolution (18 μm × 72 μm) achieved through the inkjet printing process. During this process, droplets were layered from 1 drop to 5 drops, and the experimental results confirmed that the pixels were optimally filled with 3 drops. At 3 drops, the solvent was uniformly distributed within the pixel boundaries without spilling into adjacent pixels, maintaining a stable state. This indicates that the number of drops and the solvent composition are critical factors influencing the material distribution and uniformity within the pixels in the inkjet printing process. [9]

Additionally, the image below shows the result of 300 PPI inkjet printing, where each pixel is filled with consistent size and uniform shape. These results demonstrate the potential of the inkjet printing process to meet the high precision and uniformity requirements necessary for high-resolution display applications. In particular, the optimized solvent and droplet number control enable independent pixel formation without interference between adjacent pixels, ensuring uniform optical and electrical characteristics across the entire display. [10-11] Then, a study on thin-film uniformity was conducted by exploring drying condition variables, including natural drying (ND), vacuum drying (VD), vacuum annealing (VA), and thermal annealing (A), to ensure uniform thin-film formation.

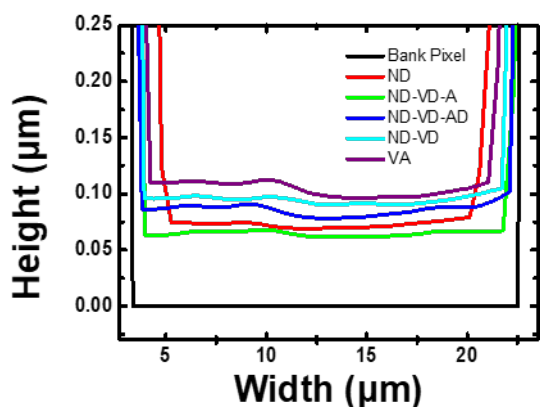


Figure 5. Variations in thin-film profiles within pixels under different drying conditions (ND: Natural Drying, VD: Vacuum Drying, VA: Vacuum Annealing, A: Thermal Annealing).

Figure 5 shows the thickness uniformity of thin films formed under various drying conditions (ND: Natural Drying, VD: Vacuum Drying, VA: Vacuum Annealing, A: Thermal Annealing). The graph illustrates the thickness distribution from the center to the edge of the film, highlighting the impact of each drying condition on the flatness and uniformity of the thin film.[12] To quantitatively evaluate the uniformity of the thin films, the Flatness Ratio (Fr) was introduced. Flatness Ratio is defined as the difference between the central thickness and the thickness at 10% from the edge, normalized by the central thickness, as follows:

$$Fr = \frac{|\text{Center Thickness} - \text{Thickness at 10\% from Edge}|}{\text{Center Thickness}}$$

A lower Fr value indicates better thickness uniformity across the film. In the ND condition, significant non-uniformity was observed due to the coffee-ring effect, leading to a higher Fr value. In contrast, VD and VA conditions showed improved thickness uniformity, with significantly reduced Fr values due to more controlled solvent evaporation. Notably, the ND-VD-A condition achieved an Fr of 0.08, the lowest among all conditions, demonstrating the best film uniformity. This result highlights that a combination of ND, VD, and A drying conditions is highly effective for optimizing film formation.[13] The A condition alone showed relatively good uniformity due to rapid solvent evaporation but may lead to micro-defects on the surface due to its high evaporation rate. These results emphasize the critical role of drying conditions in determining the flatness and uniformity of thin films. Specifically, VD and the ND-VD-A combination proved to be the optimal drying conditions for achieving uniform thin-film formation in the inkjet printing process.[14] This finding serves as a valuable guideline for designing processes in high-resolution displays and precise electronic device fabrication, ensuring both uniformity and stability in the final products.[15]

3. Conclusion

This study investigated the effect of drying conditions on thin-film uniformity in the inkjet printing process for 300 PPI high-resolution displays. The ND, VD, and A combination achieved the lowest Flatness Ratio (Fr = 0.08), demonstrating superior film uniformity. Vacuum drying and vacuum annealing were particularly effective in controlling solvent evaporation and stabilizing the thin film. For 300 PPI pixels (18 μm × 72 μm), optimal filling was achieved with 3 droplets per pixel, ensuring

stability and precise alignment. This study highlights that optimizing drying conditions and droplet control enables uniform thin-film formation, providing a foundation for high-resolution display fabrication and precision device applications.

4. Acknowledgements

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