Ink-Jet Printing Technology on Manufacturing Color Filter for Liquid Crystal Display

Part II: Printing Quality Improvement

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Abstract

This study discloses a novel application of Ink-Jet printing technology on manufacturing color filter for LCD. With the special inks invested by ITRI (Industrial Technology Research Institute, Taiwan), by using this system with OES self developed head, a strip-type color filter (pixel size 113 µm * 339 µm, with 20 µm black matrix width) made by ink-jet printing method is achieved. The results show that the accuracy of motion and printing are satisfactory. However, the innate characteristics of satellite drop problem by ink-jet method reduce the yield rate. In this study, a driving waveform control method is provided to modulate the ink discharging condition; the preheating and inter-cooling function are elaborate to improve the printing quality. Experimental observation shows a significant reduction in satellite drop and its position deviation, and the dots circularity is acceptable.

Introduction

Drop-on-demand printheads have emerged as one of the main printing technologies in recent years, especially for industrial applications. Two categories of ink jet print heads that are commonly used are piezoelectric ink jet (PIJ) printhead and thermal bubble ink jet (TBIJ) printhead. This study focuses on the application of manufacturing color filters by a drop-on-demand TBIJ printer. Color Filter is an important constituent of liquid crystal display panel. It consists of a number of filter elements, each has R, G, B color portions and black matrix (BM) is located between the colors. The black matrix is a light-shield material used for isolating color-mixing and enhancing the contrast. Color filter generally requires high color purity, high transmittance, high contrast, low reflection, and high stability against heat, light, and chemical. There are four known methods to make color filter, the dyeing method, the pigment dispersion method, the electro-deposition method (ED), and the printing method. For the fore mentioned methods of fabrication, they not only require complex processing and expensive equipments but also have the limitation in the size of color filter. In addition, the yield decreases as the process and size increases. This relationship leads to very high production cost and a large amount of material waste.[1]

To solve the problems above in manufacturing color filter, an ink-jet printing color filter system is developed.[2-3] The process is composed of compact equipment and reduces the process time. Further, it enables us to consume the minimum volume of ink. The manufacturing processes include steps of ejecting ink of predetermined colors in a plurality of filter elements concavities, which are formed in a predetermined pattern on a template to build a color pattern layer. This technology has the potential to replace traditional methods for making color filters. However, to eliminate color mixing between adjacent color elements induced by drop position deviation and satellite problem, the ink drops must be exactly discharged into the center of the filter elements, and the satellite drop should be as possible as reduced. The former problem results in a defective color filter with white omission and the latter results in low production rate. White omission is a serious defect for color filter, and causes deterioration in image quality. Therefore, the ink-jet technology must improve printing quality when applied in color filter manufacturing process. It leads to the requirement of a high-accuracy position control system to align the position shift between filter elements and printing nozzles, and a head driving method to modulate the jetting condition.

The printing quality of a thermal inkjet printhead is significantly affected by droplet ejection performance. Therefore, factors affecting the droplet ejection process should be carefully investigated. Asai et al. (1987) conducted both numerical simulation and experimental measurements to obtain the temporal variation of the ejected droplet length. Chen et al. (1997) used a one-dimensional model to describe the unsteady heat conduction problem, bubble growth, and ink motion of the top-shooter thermal inkjet printhead. Their results show that the threshold operating voltage for ink ejection decreases with the heat pulse width increasing. In addition, increasing the operating voltage causes a little volume change of the ejected droplet at a fixed heating pulse width. Therefore, the droplet volume is only slightly affected by the variation of heating pulse if the operating voltage is kept at a constant value.

Experimental Apparatus

This study has established an apparatus to modulate and control the printing. The coloring processes are performed individually for each color, thus it reduces the calibration time of position between different color heads. The system is based on a three-axis X-Y-θ table, a set of printing head, and an area CCD are fixed on the mechanical support. The set of the print heads includes red, green, and blue print heads above the platform. Each motion axis equips a 5-phase stepping motor with micro-step resolution of 0.5 μm, and maximum moving speed of 5 in/s. A rotary stage (X-Y plane) is positioned to rotate the substrate in θ direction, and the rotating range is within ±3° with step resolution of 0.0025°. This apparatus is supported on a granite base (AA Grade, 900*600*125mm) with four vibration isolators to absorb the vibration. A PC-based controller is used for controlling overall operation of the manufacturing process. In operation, the firing distance between substrate and print head is adjusted at 500 μm. Conceptually, shorter distance will ensure the satellite drop land within an acceptable range, and the deviation of discharged at position is decreased. However, a distance that is too close may lead to scratch on the substrate, because the substrate surface is not perfectly flatness. This distance is determined based on experimental adjustment. The substrate used for satellite observation testing is transparent film, and for the color filter ink-jet printing sample is the glass substrate with photo bank, as described in Part I.[7]

Thermal Ink Jet Behavior Description

The concept of using steam to drive a drop-on-demand inkjet device had been mentioned first by Stemme in 1973 patent,[8] and late to 1981, Canon demonstrated the first two color, 200 dpi, computer line printer, begins the era of thermal ink jet. The thermal ink-jet head (TIJ) is a heater located in the floor of an ink channel near the exit nozzle. Two major heater designs are the roofshooter type and the edgeshooter type, respectively. The basic flow behavior mechanism is the same. When the driving energy (voltage pulse) is applied to the heater, warming the ink contact with it sufficiently for an ink component to boil. Film boiling and micro-bubbles formation begin at ~ several μs after the voltage pulse starts, and these micro bubbles concatenate form a full bubble completely in about tens of μs. The full bubble will push the liquid to jet and the drop formation. This liquid to vapor transition results in a very great volume expansion of the heated liquid. Pressures of ~100 atmospheres are generated pushing a drop out of the nozzle. Then the drop continues to break off and the bubble collapses back onto the heater.[9] The process is repeatable and reproducible depend on the refill dynamics of ink. In this study, to improve the printing quality of a TIJ head, especially for reduction of satellite appearance and position deviation, a driving pulse modulation method is designed. The strategy will describe in below.

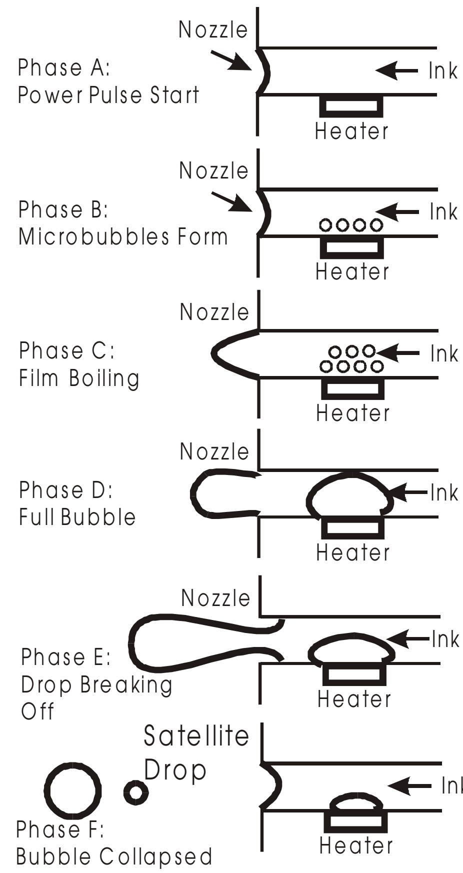


Figure 1. An idealized TIJ drop ejection sequence.

Printing Quality Improvement Method

Head Altitude

The most serious problem in using ink-jet method to make color filter is the satellite droplet comes with main drop. It often travels more slowly and along slightly different angular trajectories than does the main drop. It randomly distributes on a continuous droplet track. This behavior causes serious problem such as color mixing and reduce the yield rate. In the worst situation, the satellite drop can far away from main drop of 100 μm. For strip type color filter, it affects the horizontal direction minor, but makes the color mixing in vertical direction. It is found that the bigger the firing distance is, more time is allowed for the satellite's landing point to migrate out from the diameter of the main drop spot. A simple and straightforward solution is to adjust the distance between the print head and the substrate closer so the satellite drop spot can hide within that of the main, their relationship can explain in Fig.2. In this study, it was found that height between print head and substrate surface reduces will significantly inhibit the deviation of satellite drop from main drop. A typical value of 500 μm height is accepted in this study.

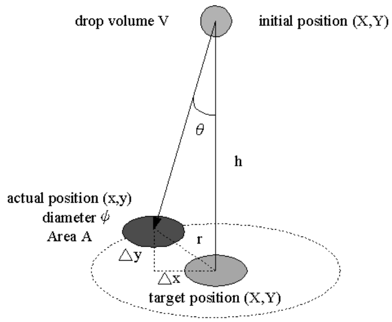


Figure 2. Relationship of print head nozzle and ink droplet landing. Notation: h→Head height above glass substrate. θ →Shooting angle. R→ Position deviation. V→ Drop volume. A→Dot area.

Waveform Control

In this study, the ink-jet method to make color filter is feasible, however, the satellite drops occurrence reduce yield rate. Typical Example is shown in Fig. 3. These spots in Fig. 3 are the satellite drops that crossed over to another color portion, it made the color-mixing problem. The satellite drops present random, it is caused by the break-off behavior of jetted drops. To reduce the occurrence probability and deviation of satellite drop, the interface of ink-head should be modified, some known skill such as reduce ink viscosity, rise ink surface tension, and change the material of nozzle plate etc. Besides, by fine-tuning the driving signal, the satellite drop will be significant reduce, as describe below.

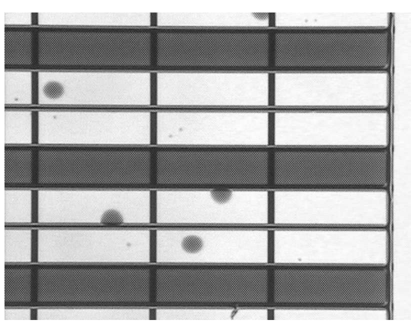


Figure 3. Color Filter with satellite drops occurrence.

This study presented a head driving method to reduce the satellite drops occurrence. It was based on two concepts from thermal ink-jet behavior as had shown in Fig. 1. The first concept is to create more micro bubbles during phase B-C before phase D. Here we designed a driving waveform with a step cooling, called as inter-cooling stage, to extend the micro bubbles creation time during phase B-C. More micro bubbles will build strong full bubble and the push force on ink will be intensified. Thus, the jetting behavior will significantly improve by the higher jetting velocity and prolonging break-off point.[10] It makes the less position deviation of main drop and the creation of satellite drop. The second concept is to preheat nozzle during printing, called as preheating stage, to keep the printing stability. It is because the heater temperature can be preheated during each firing, and the heater condition can keep at the same stable condition. Besides, the preheat function will oscillate the ink at nozzle surface, to refill ink to compensate the vaporization of ink. The vaporization of ink at nozzle surface will increase the ink concentration and make nozzle kogation. The preheat function can be easily made by adding several short pulses before the main driving pulse, typically, the short pulse is one of tenth to twentieth of main driving pulse is prefer.

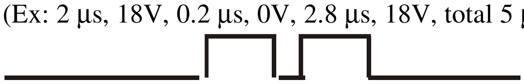
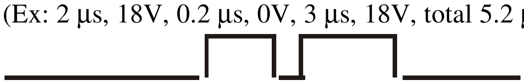
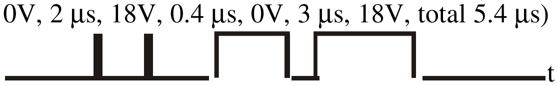
The strategy of design a waveform to drive nozzle including the preheating and inter-cooling function is described below. Here we defined a 64-bits length to modulate the waveform profile. The first 32-bits is used as preheat, and the other 32-bits is used as inter-cooling and main driving pulse energy. Each bit stands a time interval Δt. Some examples showed in Table 1.

Table 1. Examples for waveform definition.

Waveform	Example
11111111	ΔT ΔT
33333333	ΔT*2 ΔT*2
11113333	ΔT ΔT*2
77777777	ΔT*3 ΔT*3
FFFFFFFF	

Table 2 presented the decision strategy to optimize the driving condition. At step 1, the driving voltage operation range is determined by experimental observation depends on ink. The voltage level dominated the input energy to heater on nozzle. At step 2-3, we modulated different driving pulse width at the fix driving voltage to get the pulse width range, and then took the average value of step 2-3 as main driving pulse width, as step 4. Generally, based on the driving voltage and main driving pulse width, the input energy can offer the nozzle on print head to discharge ink satisfactory. At step 5-6, a driving waveform with a step cooling is designed, called as inter-cooling stage, to extend the micro bubbles creation time. The different at step 5 and step 6 is the former replaced a time interval of driving pulse width to low level state (0V, it means cooling, but the total pulse width is the same), and the latter inserted a time interval to low level state (but the total high level state is the same). At step 7, used the driving waveform with inter-cooling stage, the preheat function is added before the main driving pulse width, to keep the nozzle firing stable, as showed in Table 2. The preheat pulse segmentation and width is determined by experimental observation. Table 3 presented the experimental results. The blue color filter ink and OES-I print head are used for testing. The modulation method is followed the procedure as described and showed part of the experimental results in Table 3.

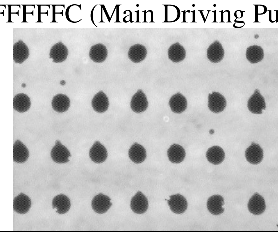
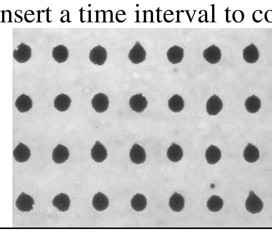
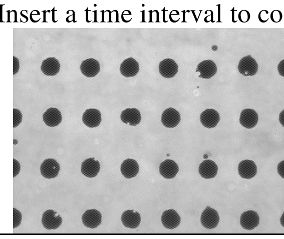
Table 2. Decision strategy for optimizing driving waveform.

Step	Description
1	Set the driving voltage to constant (EX: 18V)
2	Determine the minimum driving pulse width (Observation: Ink dot presented) (Ex: 3 μs, 18V) 
3	Determine the maximum driving pulse width (Observation: Ink dot begins scattering & spreading.) (Ex: 7 μs, 18V) 
4	Take the average of step 2-3 as the main driving pulse width.(Ex: 5 μs, 18V) 
5	Keep the same main driving pulse width, instead of partial Δt as inter-cooling stage (Ex: 2 μs, 18V, 0.2 μs, 0V, 2.8 μs, 18V, total 5 μs)  **Inter-cooling**
6	Insertion several Δt as inter-cooling stage to main driving pulse (Ex: 2 μs, 18V, 0.2 μs, 0V, 3 μs, 18V, total 5.2 μs)  **Inter-cooling**
7	Determine a optimizing inter-cooling condition (Ex: 2 μs, 18V, 0.4 μs, 0V, 3 μs, 18V, total 5.4 μs)
8	Insertion preheating stage before the main driving pulse
9	Determine a optimizing preheating condition (Ex: 0.1 μs, 18V, 0.1 μs, 0 V, 0.1 μs, 18V, 0.1 μs, 0V, 2 μs, 18V, 0.4 μs, 0V, 3 μs, 18V, total 5.4 μs)  **Preheating** **Inter-cooling**

Discussion & Conclusion

This study discloses a novel application of Ink-Jet printing technology on manufacturing color filter for LCD. With the special inks invested by ITRI (Industrial Technology Research Institute, Taiwan), by using this system with OES self developed head, a strip-type color filter made by ink-jet printing method is achieved. The results show that the accuracy of motion and printing are satisfactory. However, the innate characteristics of satellite drop problem by ink-jet method will reduce the yield rate. This observation suggests the height between the substrate and print head should be closer to hide the satellite spot within main spot. A typical value of 500 μm height is accepted in this study.

Table 3. Results for driving waveform modulation.

Waveform	Comment
FFFFFFFC (Main Driving Pulse) 	Satellite drops occur apparently & dot circularity is bad.
FFFF3FFC (Insert a time interval to cool) 	Less satellite drop & position deviation reduced
00011000 (Preheat)+FFFF3FFC (Insert a time interval to cool) 	Satellite drop presence & dot circularity is improved

The ejection performance and printing quality of a thermal inkjet printhead are significantly affected by bubble growth dynamics. Yang et al (2002)[10] investigated bubble growth dynamics and the ink ejection process under various heating conditions that are controlled by driving voltages. Their numerical computations suggest that a three-step voltage control method results (inter-cooling in this study) in a larger ink-ejection velocity than one-step voltage control method, even though the former generates less thermal energy. Through simulation, it can be shown that the three-step voltage control method actually has a larger heat flux rate from the printhead heater to the ink chamber when the ink is nucleated. Therefore a larger bubble pressure and a faster ink ejection are generated.

In this study, the preheating and inter-cooling function are elaborate to improve the printing quality. Experimental observation shows a significant reduction in satellite drop and its position deviation, and the dots circularity is acceptable. However, more study is required to keep improving the printing stability and the print head kogation problems in industrial applications, especially for the ink-jet color filter and PLED (Polymer Light Emitting Device).

So far, the yield rate of ink jet method cannot compete with semiconductor processes; it needs more improvement on the ink formula, print head architecture, and substrate design. Moreover, the arbitrary waveform driving method, for example, a square wave followed by a triangle wave, or a multi-steps voltage regulation wave, is suggested to further fine-tuning the print quality.

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Biography

Kevin Cheng received his B.S. degree in Mechanical Engineering from the University of Tamkang at Taiwan in 1992 and a Ph.D in Aeronautics & Astronautics from National Cheng Kung University in 1998. He is now a system integration section manager in the Printing Technology Division, Opto-Electronics and Systems Laboratories of Industrial Technology Research Institute at Taiwan. His work has primarily focused on the system integration and industrial ink-jet printing processes development, such as color filter, Polymer Light Emitting Device (PLED), micro-lenses, organic TFT by ink-jet printing, etc. E-Mail : ChaoKaiCheng@itri.org.tw