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

Part I: Ink-Jet Manufacturing Processes

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Abstract

A manufacturing process is developed to make color filter by discharging the predetermined color ink to the substrate, and then curing the discharged ink to form the color filter pattern. In this paper, an ink-jet printing apparatus with drop on demand multi-nozzle heads was set up to manufacture color filters. The apparatus includes a X-Y-θ table supporting the substrate, and a set of drop-on-demand ink-jet heads arranged on the adjustable Z-axis for coloring the filter elements. The special inks invested by ITRI (Industrial Technology Research Institute, Taiwan), by using this system with OES self developed print 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 color coordinates of three colors (red, green and blue) on the chromaticity diagram are (0.64, 0.35), (0.31, 0.52) and (0.13, 0.13). The transmittance for red, green and blue is 90%, 80%, and 85%, respectively. Compare with commercial standard, the heat, light and chemical test results come to ΔE <5 for each color, but the alkali tests (5% NaOH & KOH) are not satisfactory. Further study to improve the ink formula is needed.

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.[1] 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. The characteristics of color filter are summarized in Table 1[4] according to these methods.[2]

Table 1. Characteristics of Color Filter

	Dyeing	Pigment	Printing	ED
Binder	A	B	C	D
Colorant	Dye	Pigment	Pigment	Pigment
Thickness (μm)	0.7-2.5	0.8-2.5	1.5-3.5	1.5-2.5
Heat Stability°C	180	220-300	250	250
Light Stability°C	<100	>500	>500	>500
Chemical Stability	Poor	Good	Good	Good
Spectrum	Best	Good	Good	Good
Surface	Good	Good	Good	Best
Resolution (μm)	7-20	10-20	70-100	10-20
Cost	Low	Middle	Middle	Middle
Processing Time	Short	Long	Long	Middle

A: Gelatin, Gasein, Acrylic, Polyimide
B : Acrylic, Polyimide, Polyvinylalcohol
C : Epoxy, Acrylic
D : Melamine, Polyester, Eopxy

To solve the problems above in manufacturing color filter, an ink-jet printing color filter system is first developed by Canon.[3] The process is composed of compact equipment and reduces the process time. 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, the ink drops must be exactly discharged into the center of the filter elements, it leads to the requirement of a high-accuracy position control system to align the position shift between filter elements and printing nozzles.

Conventionally, the ink-jet head is positioned with respect to the color filter substrate by using an alignment mark as reference, which is fabricated at the same time the black matrix (BM) is formed. The head is positioned with respect to the alignment mark. However, the BM may deviate during the manufacturing process and result in offset with respect to the head position. Besides the position error, the manufacturing process needs a lot of time in calibrating relative positions of these three printing heads (Red, Green & Blue), and the ink drops discharged on the substrate may not spread ideally on the entire surface of the filter elements. The former problem results in low production rate, and the latter results in a defective color filter with white omission. 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.

Experimental Apparatus

In view of what is described above, this study has established an apparatus to solve these problems [4]. First, the coloring processes are performed individually for each color, thus it reduces the calibration time of position between different color heads. Second, to compensate the position offset caused by the black matrix; this system will equip with a high-speed linear CCD to track the black matrix position, and it will real-time modulate the table motion to position the printing nozzles exactly above the centers of the filter elements. In the printing process, ink-jet heads scan relative to the substrate while coloring a number of filter elements. High precise pattern formation is achieved because the position of ink-drops is measured in advance by optical system to align the substrate with respect to the ink-jet heads. Thus, the position shift of ink-drop positions can be calibrated. Figure 1 shows a schematic view of the color filter producing apparatus.

The system is based on a three-axis X-Y-θ Table 16, the linear CCD 10, a set of printing head 11, and an area CCD 13 are fixed on the mechanical support 14. The set of the print heads 11 includes red, green, and blue print heads above the substrate 17. The motors 15 (one for each axis) connect to a moving stage for driving the substrate 17 in the X-Y- θ directions. In Fig.1, the X direction is defined as the direction parallel to the support 14, the Y direction as the one vertical to the support 14. Each X or Y 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 17 in θ direction, and the rotating range is within ±3° with step resolution of 0.01°. Moreover, the area CCD 13 reads the alignment mark positions to align the position offset when loading substrate, and these marks are formed on the substrate in advance. The linear CCD 10 is designed to compensate the track offset caused by the black matrix manufacturing process. The CCD reads the black matrix tracks and corrects the offset by moving Y stage in real-time. All the parts 10,11,12,and 13 hung on the support 14 are adjustable. This apparatus is supported on a granite base (AA Grade) with four vibration isolators to absorb the vibration. A PC-based controller (not show in Fig.1) is used for controlling overall operation of the manufacturing process.

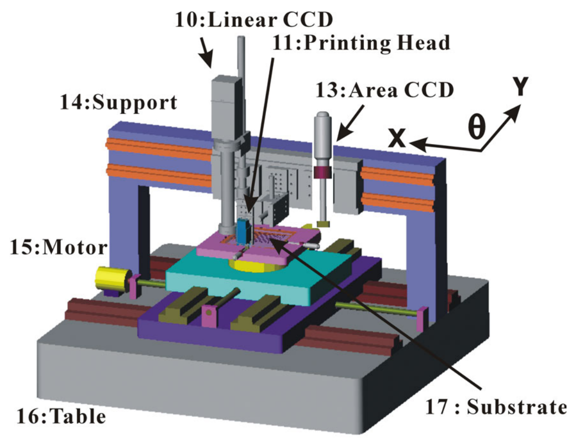

Figure 1. Apparatus Schematic

The optical system for the observation of the droplet consists of a PC-based controller with an image grabber card (National Instruments PCI-1411), and a motion control card (National Instruments PCI-7344, 4-axis) used for moving X-Y-θ stage. The optical system includes a light source beneath the substrate, a microscope with 56X magnification, and a charge-couple device (CCD) camera (Sony SSC-C370, 768*494 pixels, 470 horizontal scan lines, NTSC & RS-170 Video Output). These components were mounted in above-mentioned color filter manufacturing apparatus. The sampling rate of the image grabber card is up to 30 color frames per second (60 frames/s for black/white). Ink-jet heads scan relative to a substrate that was driven by X-Y-θ axis motors. The optical scale resolution is 0.5 μm for X-Y axis, and 0.002 degree for θ axis. 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.

Color Filter Pattern

Generally, a color filter consists of clear substrate, black matrix, color filter layer (RGB colors), overcoat layer and ITO film. The clear substrate is generally thin glass or plastic. The black matrix material is deposited on clear substrate in the optically inactive areas to prevent light leakage and provide a light shield for the amorphous silicon transistors. The black mask material should have a low reflectance to optimize contrast ratio. Black matrix material can be organic or inorganic, with chromium a most popular inorganic choice. The color filter layer is fabricated which contain red, green and blue colors from either dyes or pigments. After the color layer is formed, protection overcoat layer is deposited. Transparent acryl resin, polyimide resin or polyurethane resin is used for overcoat material. The purpose of overcoat layer is the reduction of color pattern's thickness variation, durability against sputtering and chemical resistance. The overcoat layer is important for dyeing CF and printing CF. In the dyeing CF, the over-coat layer is necessary to protect the liquid crystal from impurities in the CF layer and to increase the chemical stability. In printing CF, the overcoat layer flattens the CF surface. For the pigment dispersion method has enough hardness, the overcoat layer is not necessary, since it increases the process step and production cost. Indium tin oxide (ITO) is finally deposited at low temperature (200°C).[5]

It is an extremely important requirement of color filter for LCD applications. It depends on what materials and manufacture process are used. The most requirements such as the high color purity and high transmissivity, the high contrast, low reflection, high stability against heat, light and chemical.

Two major type of color filter are designed in general. Fig. 2 expounds the patterns of color filter. The first one is the strip type, as shows in the second row. It is the simplest color filter pattern and easy to design. The other is the mosaic type. The different color is arranged adjacent to the others colors. Many mosaic type color filter patterns have been developed for various applications, as shows in Fig. 3. Some of these patterns are in direct RGB color space and are denoted by R (Red), G (Green) and B (Blue). Some of patterns are in complementary color space and are denoted by CY (Cyan), MA (Magenta), and YE (Yellow). In this study, we focus on the strip type color filter.[6]

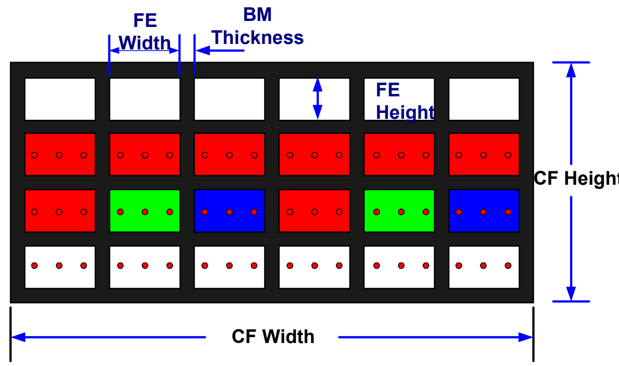

Figure 2. Color Filter Pattern

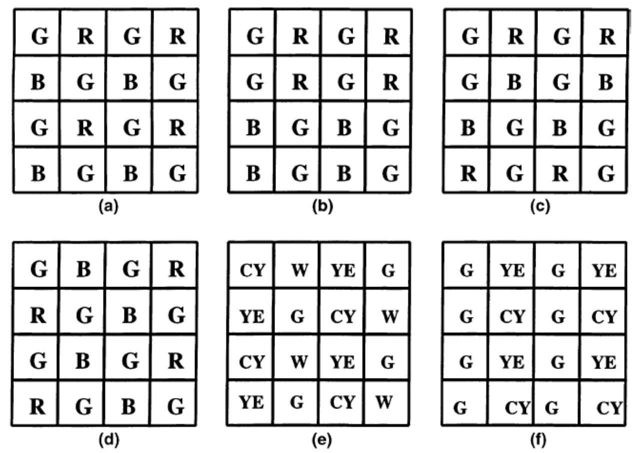

Figure 3. Different color filter patterns. (a) Bayer (b) Modified Bayer (c) Green checker field sequence (d) Kodak (e) Hitachi (f) Toshiba

Manufacture Processes

This study presents a standard strip type color filter (1024*768 pixel resolution, 15" XGA Stand) made by ink-jet as shown in Fig. 4. In Fig. 4, the red, green, and blue color is printed on glass substrate with black matrix (black lattice structure in Fig. 4). Each block (contain one red, green, blue pixel, and black matrix boundary) has size of 339 μm*339 μm.

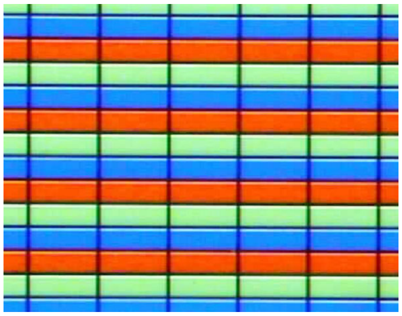

Figure 4. Color filter made by ink-jet method in this study.

Glass Substrate and Color Filter Ink

The glass substrate is a non-alkali glass (In general, Corning 1735 or 1737 type) in 5 inches diameter. To keep the surface clean, it is immersed in Acetone for 5 minutes first. The printing color filter size is 3"*3" square in strip type pattern. Each color has the filter element height of 93 μm, and the black matrix (BM) width is 20 μm. As shows in Fig.4. Color ink used in this study was water-based dye. Ink formulas consist of the pigments (Red, Green, and Blue, ~2-16%), binders (~21.5%), humectant (To keep moisture in printing, for example, 2-pyrrolidone, 10-15%), water (~50%), and additives (~4.0%). The additives include solvents, surfactants, viscosity modifiers, UV initiator, UV inhibitor, UV oligomer, and UV monomer. The most important properties for ink-jet printing are the ink surface tension and viscosity. It affects the jetting process of print head. In this study, these three-color inks are modulated in the value of 7-18 CPS (viscosity) and ~35 dyne/cm (surface tension). The pH is in the range of 6-8. Figure 5 showed the spectrum for red, green and blue color. It indicated that the blue and green is satisfactory match with most commercial product, but the red color is broadband in short wavelength.

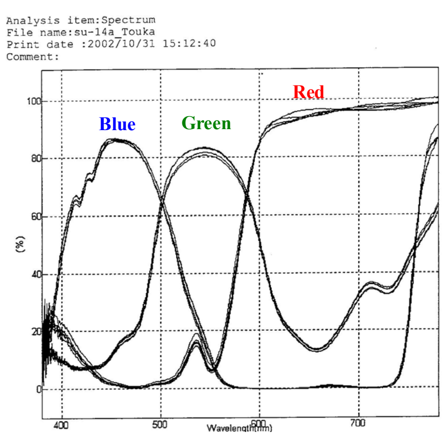

Figure 5. Color Spectrum for Red, Green, and Blue.

Black Matrix & Lithographic Processes

Table 2 described the process parameters used for this study. The metal Cr as black matrix has an optical density (O.D) of 3.3. The SU8-2005 photoresistor was used for bank structure. It consisted by the process of spin, 2-steps softbaking, exposure, 2-steps post baking and developing. The detail parameters can refer Table 2.

Table 2. Process parameters for black matrix and bank.

Clean	By Acetone & IPA
Cr Deposition	O.D ~3.3 1500Å
Spin Coating (SU8-2005)	1. RPM500/5S 2. RPM3000/30S
Soft Baking by Hot Plate	65°C/1 min
Soft Baking by HOT PLATE	95°C/3 min
Exposure (Karlsuss-MA6)	23S (120 mJ/cm^2)
Post Baking by Hot Plate	65°C/1 min
Post Baking by HOT PLATE	95°C/3 min
Developing (SU8-developer)	1 min

Ink-Jet Printing & Post-Treatment Processes

In Fig. 4, the color inks drops are continuous and accurate to be discharged into the glass substrate, and then the ink wetting along the shield bank (a transparent repellent-water wall constructed on horizontal black matrix, the wall height is controlled about 5 μm). The wetting capability depends on the characteristics of ink and glass substrate, likes the substrate surface roughness, substrate surface tension, and ink surface tension.

Before Printing, a pre-baking processes operated at 190°C for 3 min, and then discharging the color ink B, R, G, respectively. After printing, these three inks were cured by heat treatment (Barnstead / Thermolyne SP47235) at 150°C for 5 minutes, and then cured by UV light (Hamamatsu Lightningcure 2000) at power of 3500 mW/cm^2 (365 nm) for 5 minute. The curing processes will solid and form color film on the glass substrate. Similar process can repeat till three colors are form on the glass, as the color sample shows in Fig. 4.

Discussion

Chromaticity Diagram & Thickness Analysis

Figure 6 presented a cross-section profile of strip type bank over on BM. It indicated that the bank has width 18 μm and height 4.6 μm, as shown in Table 3. The A-E indicated the different measured position on panel, where A, B, D, E were located at corners, and C at center of panel. It is noticeable that the bank width is less than the width of BM. In this design, the bank width is less than BM width about 1 μm, to make a step effect to prevent the colorant wettability. The concept of design bank width is limited by two factors, one is the step effect, and the other one is the aspect ratio. For step effect, Canon's patent[7] (USPTO 6183917) suggests that the bank and color portion has an angle of 70-88 degree is better, therefore, in this study, the angle between the color portion and bank is about 78 degree ($\tan^{-1}$ (4.66)). As shown in Fig. 6, it is found near the interface of bank wall, the colorant (Blue is here) will form concave profile because the little hydrophilic behavior. It made the flatness of colorant varied from 0.86 µm (center) to 1.14 µm (edge). Further modified the bank (hydrophobic) and substrate (hydrophilic) to make more flat-film quality is needed.

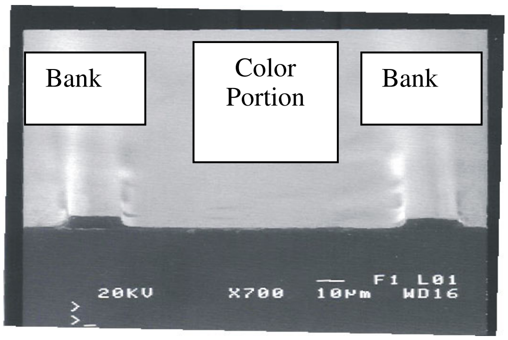

Figure 6. Cross-section profile of bank and colorant.

Table 3. Measurement of Bank Thickness for SU8-2005, unit µm.

Position / Times	1	2	3	Average
A	4.64	4.67	4.62	4.643
B	4.64	4.67	4.65	4.653
C	4.61	4.63	4.64	4.626
D	4.61	4.61	4.58	4.6
E	4.65	4.65	4.68	4.66

Table 4 and Fig. 7 presented the CIE coordinate for this ink-jet fabrication color filter. The color coordinates of three colors (red, green and blue) on the chromaticity diagram are (0.64, 0.35), (0.31, 0.52) and (0.13, 0.13). The transmittance for red, green and blue is 90%, 80%, and 85%, respectively. The triangle area is about 40% of that of NTSC standard.

Table 4. CIE coordinate for this measurement

Item	R	G	B
NTSC	(0.67, 0.33)	(0.21, 0.71)	(0.14, 0.08)
OES	(0.64, 0.35)	(0.31, 0.62)	(0.13, 0.10)

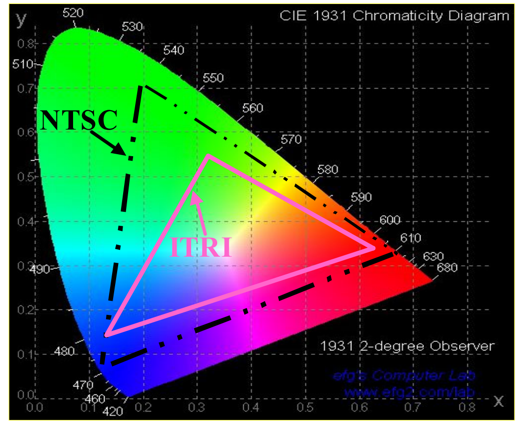

Figure 7. CIE coordinate for this measurement.

The color filter sample made by ink-jet method then post-treated by UV curing and baking. Its quality was verified through heat, light and chemical testing, as shown in Table 5. Compare with commercial standard, the heat, light and chemical test results come to ΔE <5 for each color, but the alkali tests (5% NaOH & KOH) are not satisfactory. Further study to improve the ink formula is needed.

Table 5. Color filter heat, light and chemical testing results

Test Item	Condition	Result
Heat	250°C, 1 hr	All ΔE <5
Chemical	18% HCl, 40°C, 30 min	All ΔE <5
Chemical	5% NaOH, 23°C, 30 min	Fail
Chemical	5% KOH, 23°C, 30 min	Fail
Chemical	g buthyl-lartone , 79°C, 10 min	All ΔE <5
Chemical	IPA, 23°C, 30 min	All ΔE <5
Light	365 nm, 10 min	All ΔE <5
Transmittance	Red Color, 1µm	>90%
Transmittance	Green Color, 1 µm	>80%
Transmittance	Blue Color, 1 µm	>85%

Conclusion

In this study, an ink-jet printing apparatus was setup to manufacture color filters. The apparatus includes a X-Y-θ table supporting the substrate, and a set of drop-on-demand ink-jet heads arranged on the adjustable Z-axis for coloring the filter elements. The mechanical motor drivers provide movements for the relative displacement of the substrate with respect to the ink-jet head.

This study discloses a novel application of Ink-Jet printing technology on manufacturing color filter for LCD. With the special-purpose inks and the ink-jet printing apparatus developed by ITRI (Industrial Technology Research Institute, Taiwan), 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 color coordinates of three colors (red, green and blue) on the chromaticity diagram are (0.64, 0.35), (0.31, 0.52) and (0.13, 0.13). The transmittance for red, green and blue is 90%, 80%, and 85%, respectively. Using commercial standard, the heat, light and chemical test results come to DE <5 for each color, but the alkali tests (5% NaOH & KOH) are not satisfactory. This study suggests that the bank surface need to be more hydrophobic to prevent ink-wetting behavior. And further study to improve the ink formula and the flatness of colorant film are also needed.

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Biography

Wanda W. W. Chiu received her Master degree in Mechanical Engineering from National Cheng Kung University in 1996. She is now a system integration engineer in the Printing Technology Division, Opto-Electronics and Systems Laboratories of Industrial Technology Research Institute at Taiwan. Her work has primarily focused on the industrial ink-jet printing processes development, especially in color filter and color filter on array by ink-jet printing. E-Mail: wandachiu@itri.org.tw