13

Photolithography

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13.1 INTRODUCTION

Photolithography is a technique that can be applied to form precise patterns in metal, oxide, nitride, and semiconductor films during the fabrication of the TFT arrays and color filters. The precise and fine patterns on a photomask are accurately transferred by UV irradiation through the photomask plate into to a photoresist material coated as a layer over the film to be patterned. The patterns recorded into the irradiated (exposed) photoresist appear after the development process, and then wet or dry etching is employed to etch out the underlying film through the window areas created in the locations where the photoresist was removed during the development process. The photoresist acts as a mask during the etch step protecting the underlying portions of the film. The final patterned film with the desired structural design is obtained after the remaining photoresist mask is completely removed by a photoresist stripping process.

The main processing steps in photolithography include (1) pre-cleaning, (2) photoresist (PR) coating, (3) pre-baking for PR hardening, (4) exposure, (5) development, (6) post-baking, and it is completed with (7) etching, (8) PR stripping and (9) post-cleaning. For high volume manufacturing operation, the photolithography equipment usually adopts a design with an in-line architecture where all the stations for pre-cleaning, PR coating, pre-baking, exposure, PR development through post-baking are connected together in a so-called "photoresist track system" to allow high throughput inline motion of glass substrates. One end of the photoresist-track system is connected to the exposure system, and the loader/unloader station is installed at the other end. The equipment for wet/dry etching and stripping equipment is installed in separated zones, to which the glass substrates are automatically handled and conveyed.

In this chapter, the main in-line processes from photoresist coating to development for performing photolithography for the TFT arrays and color filters are discussed. The key materials used in photolithography are photoresists and development solutions. First of all, an overview of photolithography for TFT arrays is given, followed by photoresist coating methods and equipment, focusing on the slit coating that is suitable for over Gen 6 glass substrate sizes. Then, the exposure process is discussed with detailed explanations on the four main types of exposure equipment (stepper (Nikon), multi-lens scan (Nikon), mirror projection (Canon), and proximity), as well as photoresist materials and UV light sources. For the large size exposure in TFT arrays

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over Gen 6 sizes, both lens scan and mirror projection are available. Puddle development is the major approach for over Gen 6 size TFT arrays. Finally, photolithography for color filter manufacturing is discussed.

13.2 PHOTOLITHOGRAPHY PROCESS OVERVIEW

Photolithography is the process which forms the masking layer for etching and ion doping using photosensitive materials called photoresist (PR), in the so-called "patterning" process. Using photolithography, the pattern of the photomask can be transferred into a desired film that is coated on the substrate. Photolithography can be applied for the patterning of TFTs, bus-lines, via-holes, pixel electrodes, and so on, for TFT arrays, for the patterning black matrix (BM), R G B color filters, photo-spacer for the color filters arrays, as well as patterning for touch panels. The key process steps in photolithography are shown in Figure 13.1. In this section we discuss in details the process flow and each of the unit processes in photolithography.

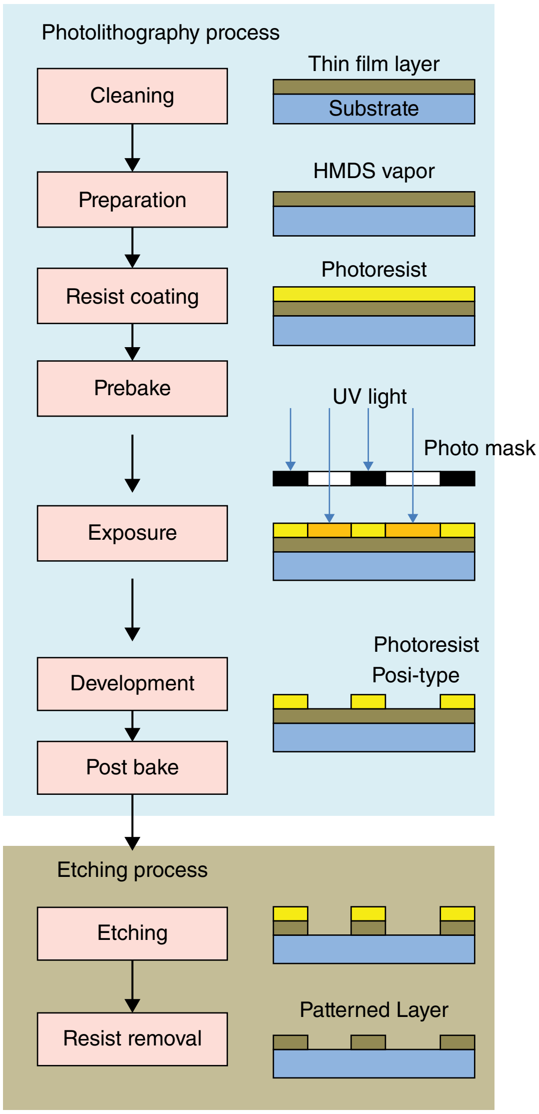


Figure 13.1 Overview of photolithography process flow.

13.2.1 Cleaning

The cleaning process is employed to remove particles and contamination from the surfaces of the substrates. A suitable cleaning process can be selected from various washing methods including mechanical cleaning (e.g., brushes, high-pressure sprays), chemical cleaning, UV or plasma cleaning, deionized water (DIW) rinsing and others, depending on the conditions of the glass substrate surfaces.

13.2.2 Preparation

The substrate is initially heated up to a sufficiently high temperature to drive off any moisture that may be present on the substrate surface (dehydration baking). Further, a liquid or gaseous "adhesion promoter," such as HMDS (hexamethyl-di-silazane) is typically applied to promote adhesion of the photoresist to the substrate.

13.2.3 Photoresist Coating

The photoresist layer is uniformly coated on the substrate by spin or slit coating a photoresist solution. Positive-tone photoresist, the most common type, is used for TFT array patterning to get fine patterns. For color filter fabrication, a colored resist (usually negative tone) is commonly employed.

The photoresist-coated substrate is dried in vacuum for accelerated processing, and then prebaked to complete removing the excess solvent, typically at 90–100 °C for 30–60 seconds on a hotplate.

13.2.4 Exposure

After pre-baking, the photoresist layer is irradiated with intensive UV light through a photomask having an opaque layer patterned with the same pattern as the image intended to be transferred onto the substrate using the exposure system (photoresist exposure step). For positive-tone photoresist materials, the UV irradiated area becomes soluble in the basic developer solution, whereas for negative tone photoresists the exposed region becomes insoluble in the organic developer used for the negative photoresist.

13.2.5 Development

After exposure, the photoresist layer is developed using a developing solution (or developer). For positive photoresists, TMAH (tetra-methyl-ammonium hydroxide) solutions are used as the developer, and an appropriate organic solvent is used for the color resist. Upon development, the pattern designed on the photomask is formed as a physical PR pattern, after regions of the PR material are dissolved away. Then, the substrate is "post-baked," typically at 120 180 °C. The post-baking solidifies the remaining photoresist, to increase its robustness as a protecting layer during subsequent wet or dry chemical etching steps.

13.2.6 Etching

The wet and dry etching processes are discussed in Chapters 14A and 14B, respectively.

13.2.7 Resist Removal

After etching the film covered by photoresist mask, the hardened PR material is stripped away (removed) using a resist stripping chemical solution. Subsequently, the substrate is cleaned again with a rinsing agent and DIW.

13.3 PHOTORESIST COATING

13.3.1 Evolution of Photoresist Coating

The methods used for photoresist coating on glass substrates have evolved from (1) spin-coating, (2) slit and spin-coating, to (3) slit-coating, as shown in Figure 13.2, as the dimensions of the display glass substrates increased through manufacturing generations.

Spin-coating has been used in up to Gen 4 size plants. It employs dropping an appropriate volume of PR solution onto the center of a spinning substrate, relying on the centrifugal force to spread the solution and leave on the substrate a uniform film coating with thickness dependent on the spinning speed. However, since only about 10% of the dispensed photoresist solution remains on the substrate after spin-coating, the wasted 90% of PR becomes a serious issue as the size of the glass substrate increase.

Slit and spin-coating has been developed for Gen 4/Gen 5 size plants. In this method a slit coater is used to first coat the photoresist over the substrate with approximate thickness, and then spinning is applied to produce a photoresist layer with a highly uniform thickness. Photoresist consumption by using slit and spin-coating can be reduced down to one third of that by using spin-coating.

As glass sizes processes in Gen 6 size plants and beyond have become even larger, the methods involving spinning are is no longer used. Later on, improved slit-coaters using newly developed slit nozzles with high-precision mechanisms have been developed. Such slit-coaters are capable of not only generating highly uniform photoresist layers, but also reducing photoresist consumption down to as low as less than one-tenth of that by spin-coating. The details of such slit-coating are further discussed in the next section.

13.3.2 Slit Coating

13.3.2.1 Principles of Slit Coating

Figure 13.3 shows the schematic diagram of a slit-coating system. In this system, the photoresist solution is dispensed onto a glass substrate through a moving slit nozzle (with a linear opening as wide as the target-coating width on the substrate). First, the nozzle is positioned at the start position on the substrate such that a photoresist solution bead forms in the precisely controlled gap between the nozzle and substrate. The photoresist, as it is pumped through the nozzle, stays around the bead on the substrate for a short period of time and then is carried away with the motion of the substrate at a predetermined constant speed that instantly matches the volume of the photoresist that has just been carried away with the moving substrate. This bead structure and behavior, which is dependent on the up- and downstream menisci and on the gap thickness, are critical to achieving high stability and uniformity of the resultant photoresist films. To achieve best optimized results, delicate balance among all the factors related to the width of the slit nozzle, coating gap, moving

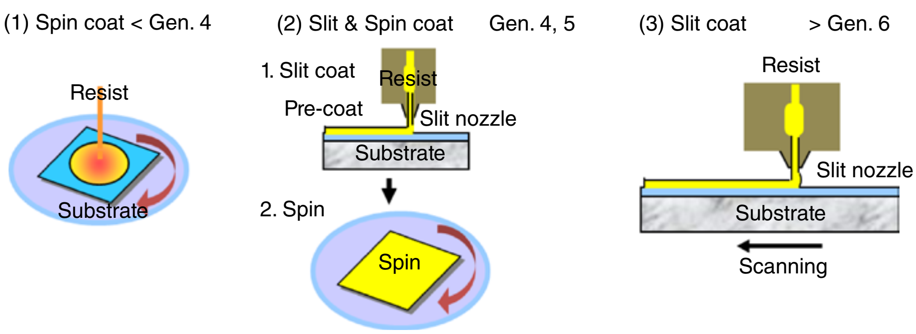


Figure 13.2 Evolution of photoresist coating processes for glass panel substrates.

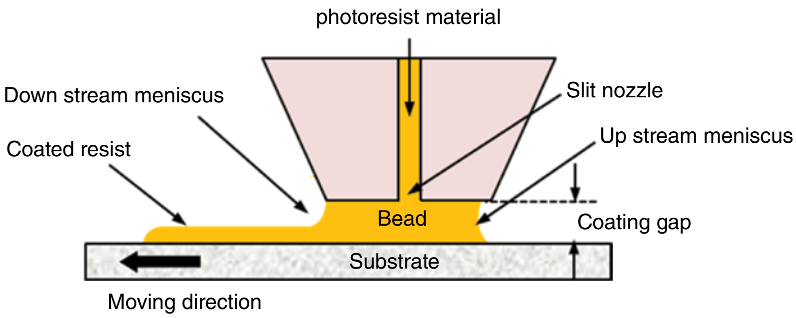


Figure 13.3 Conceptual diagram of slit-coating process.

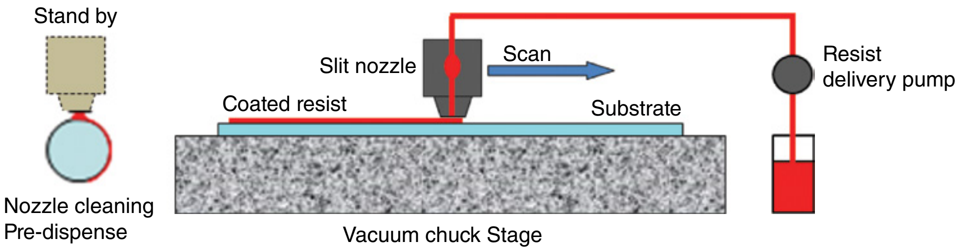


Figure 13.4 Diagram of a slit-coating system (*Source:* Courtesy of Screen Finetech Solutions).

speed, viscosity of the photoresist, and coating atmosphere is required. In slit-coating it is necessary to use PR solutions with a lower viscosity than those used in spin-coating (Figure 13.4).

13.3.2.2 Slit-Coating System

A slit-coating system can uniformly coat the dispensed PR solution onto a glass substrate (typically vacuum-chucked) by dispensing the solution with a predetermined flow rate, keeping the gap between the nozzle and substrate constant when the slit nozzle is scanned with constant speed. The detailed structure of the slit coating system is shown in Figure 13.4. The system consists of the vacuum-chuck stage, X-Z gantry, slit nozzle, photoresist delivery system, and standby stage. The vacuum-chuck stage has a precisely leveled flat surface for fixing the substrate on the stage. The X-Z gantry can move along the horizontal direction (X-axis) with an accurate velocity and maintain the height positioning accuracy with respect to up/down direction (Z-axis) of the nozzle and a fixed gap between the substrate and nozzle head during the coating step. The slit nozzle is designed to have a constant dispensing volume with respect to the longitude direction (across the width of the substrate), and a high gap accuracy. The PR delivery system provides the photoresist fluid to the slit nozzle with a constant flow rate and fast rising response. The stand-by stage is used for maintaining the high reproducibility process, by cleaning the nozzle head after coating and pre-dispense before coating.

To perform slit-coating, the system starts with cleaning the slit nozzle and predispensing PR solution for the forthcoming coating in the standby stage. Then the slit nozzle moves to the starting point on the substrate, and the nozzle head moves again to approach the substrate and reach a narrow gap to form the PR solution bead. The photoresist is dispensed through the nozzle as the head is scanned maintain a constant gap by the system's automatic adjustment mechanisms. When the nozzle is scanned to the end point, the whole slit-coating process is completed. The nozzle head moves up, and then moves back to the stand-by stage.

With the development of slit-coating systems, it was possible to eliminate the back-rinse process needed after spin-coating for removing unnecessary PR deposited around the edges and the backside of the glass plate. Thus, by employing slit-coating, the coating cycle time can be reduced and PR consumption can be cut down to one third of that used in slit- and spin-coating.

13.4 EXPOSURE

13.4.1 Photoresist and Exposure

13.4.1.1 Photoresist

Depending on the working photochemistry, photoresist materials can be categorized into positive-tone photoresists and negative-tone photoresists. In the photochemistry engineered for positive PR, the positive-tone material exposed to the UV light undergoes chemical changes and becomes soluble in the developer liquid. Thus, the positive PR material exposed to the UV light can be easily removed by rinsing with the developer solution. Since the positive PR is suitable for obtaining finer patterns than the negative PR, it is usually employed for fine-patterning in TFT arrays. The photochemistry for negative PR materials works in the opposite way: when the negative PR is exposed to UV light, the material polymerizes and becomes insoluble in the target developer liquid. Therefore, the negative PR material exposed to UV light pattern remains on the substrate surface, while the unexposed negative PR material is removed after the rinsing process with the developer liquid.

Positive PR is a material consisting typically of a photoactive compound (PAC), base polymer, solvents and photosensitizer (PAC: NQ, amino ketone, benzo phenone etc.; base polymer: Novolac resin; solvents: PGMEA, NMP, MBA, etc.). The developer liquid is a solution based on TMAH (tetramethyl-ammonium hydroxide).

In general, the photochemistry of the negative PR involves radiation induced crosslinking. The photoactive materials employed in negative PR include vinyl, epoxy, halogen-containing polymers. Such parent polymers are usually soluble in organic solvents. Therefore, if not exposed to the UV light, the parent polymers can be removed by rinsing with the developer liquid.

13.4.1.2 Color Resist

The color resist is used to form (1) the R, G, and B pixel and (2) BM on the color filter plate. It is a negative tone PR with colored pigments dispersed in the color mill base. BM resin is used to form the black matrix pattern, and is also a negative tone PR but with dispersed light absorbers such as carbon black. Ketone, ether, and ester are the main solvents for the color resist.

The details in photolithography for the color filter fabrication will be discussed in section 13.8.

13.4.1.3 UV Light Source for Exposure

Both positive and negative PR are designed to be sensitive to UV light radiation. Mercury arc lamps are the most popular light source for exposure in the photolithography process. The emission wavelengths from the mercury arc lamp, 436 nm (*g*-line), 405 nm (*h*-line), and 365 nm (*i*-line), can work effectively for achieving the pattern resolution required for TFT-LCDs/OLEDs using the conventional photoresists.

13.4.2 General Aspects of Exposure Systems

There are three primary exposure methods: contact exposure, proximity exposure, and projection exposure. The technical factors that can affect the performance of exposure systems for TFT displays include:

(1) Image field and exposing area: area that can be exposed per shot or scan, and size of the substrate that can be exposed by a single step or multiple steps
(2) Resolution of projection optics: resolved line width and line space
(3) Alignment or overlay accuracy: the repositioning accuracy of successive exposures.
(4) Productivity (throughput): capability of processing substrates per unit time

The contact exposure method is not available for TFT display lithography due to the limitation in the size of the photomask and the damage of the photomask that can be caused by its contact with the substrate.

Table 13.1 Overview of exposure systems and key process requirements.

Process	Mask layer	Substrate size	Resolution overlay	Exposure system
a-TFT array	TFT, pixel, etc.	Any G.	$3\,\mu m$, $< 1.0\,\mu m(3\sigma)$	Mirror projection Multi-lens projection
LTPS	TFT, pixel, etc.	< G.5	$1.5\,\mu m$, $0.3\,\mu m(3\sigma)$	Stepper
		> G.6	$2\,\mu m$, $\leqq 0.5\,\mu m$)	Multi-lens projection Mirror projection
Color Filter	High resolution BM	Any G.	$3\,\mu m$, $< 1.0\,\mu m(3\sigma)$	Multi-lens projection Mirror projection
	BM, R, G, B, PS, etc.	Any G.	~$8\,\mu m$, $\leqq 1\,\mu m$)	Proximity exposure

The proximity exposure method offers high throughput processing and is less expensive due to the system's simple architecture, but its resolution is over $8\,\mu m$. Thus, it is used for exposing layers with coarse features.

The projection exposure method, which is the dominant approach in TFT display manufacturing, has three types of systems: stepper system, mirror projection system, and multi-lens projection system. The stepper system gives the highest resolution and overlay accuracy among the three exposure systems. However, as the image field of the stepper system is smaller than other systems, the throughput can be severely affected for processing large-area substrates. On the other hand, the mirror projection system and multi-lens projection system offer $< 3\,\mu m$ resolution, $< 1.0\,\mu m$ overlay accuracy, and larger image fields. Thus, the mirror projection system and multi-lens projection system are more suitable for high-throughput processing of large-area substrates.

One of the most important requirements in the exposure process is to ensure the alignment accuracy (overlay accuracy) of the photomask to allow precise fabrication of multi-layer structures such as TFTs, and CF pixel. The photomask must be precisely aligned with the substrate after the first patterning step is completed.

The exposure systems and their applications are summarized in Table 13.1.

13.4.3 Stepper

Figure 13.5 shows the schematic diagram of a stepper.

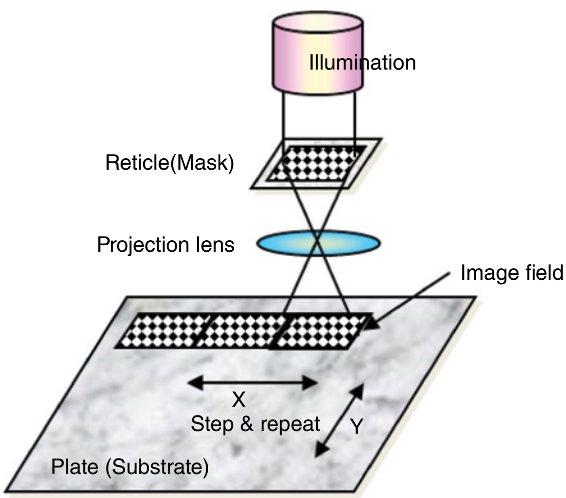


Figure 13.5 Schematic diagram of the stepper.

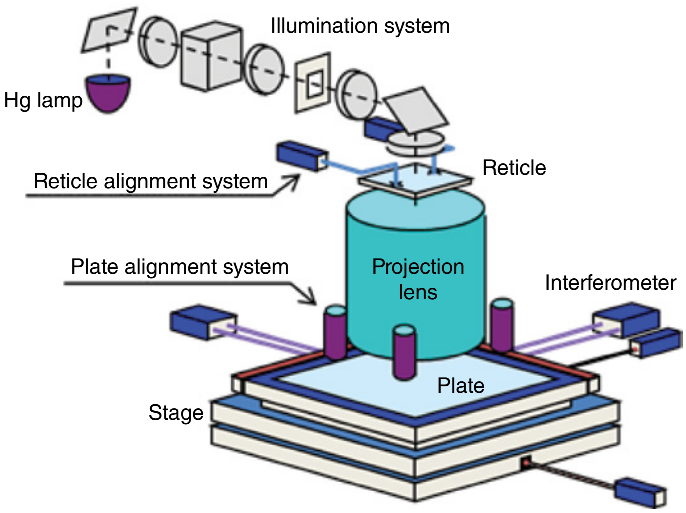


Figure 13.6 Detailed configuration of a stepper (*Source:* Courtesy of Nikon).

The pattern image on the photomask (or reticle) is projected onto the photoresist-coated substrate. In order to achieve high resolution, the projected image field per shot is limited to a small area, and this small image field is stepped and repeated over the substrate surface.

Figure 13.6 shows the fundamental architecture of a stepper provided by Nikon. It consists of multiple optical systems, such as illumination optics, projection optics, optical system to measure the focal and stage positions, and alignment optics that detects the alignment mark on the substrate, as well as the mechanical stage being capable of high accuracy motion. In this system, the UV light from the light source (high-pressure mercury lamp) passes through the illumination optics and is incident on a square reticle with the size of 6 inches. The image of the reticle is projected onto the substrate by the large aperture projection lens. The size of the projected image field is 132 × 132 mm, and that image exposes the photoresist on the substrate. This exposure is repeated by stepping in (x,y) directions to cover the entire region on the plate. At each step, the alignment between mask and substrate, and focusing on the substrate surface are controlled by the alignment and focusing systems. Thus, < 3 μm resolution and < 0.3 μm overlay accuracy can be achieved.

Resolution (R), corresponding to the accuracy of the resolving dimension, is expressed as:

$$R = k_1 \times \lambda / NA \tag{13.1}$$

k_1: process factor
NA: numerical aperture of the projection lens

In the case that NA is 0.08, k_1 is 0.6, and λ is 400 nm as a mixture light of g-h lines, the expected resolution R is around 3 μm. As shown in Equation 13.1, the resolution (R) can be improved by the increasing the aperture of the projection lens and reducing the wavelength of the illumination source. As example, 1.5 μm resolution is achieved in the Nikon FX-903N advanced stepper, based on a large aperture lens with i-line. These capabilities are especially required for small- and middle-sized display panels used for mobile applications. Table 13.2 shows the corresponding performance metrics for that stepper.

13.4.4 Projection Scanning Exposure System

For large-sized glass plates, the exposure process is achieved by multiple cycles of exposure, stepping and repeating to cover the entire glass plate. The processing throughput, especially for stepper tools, can be very

Table 13.2 Performance of Nikon FX-903N stepper system (*Source:* Courtesy of Nikon).

FX-903N Performance	
Resolution (L/S)	1.5 μm
Image field	132 × 132 mm
Wavelength foe exposure	I-line
Projection magnification	1 : 1.25
Alignment accuracy	0.3 μm (3 σ)
Max. plate size	730 mm 920 mm
Reticle size	6 inches
Take time	61 sec (30 shots, 50 mJ/cm^2)

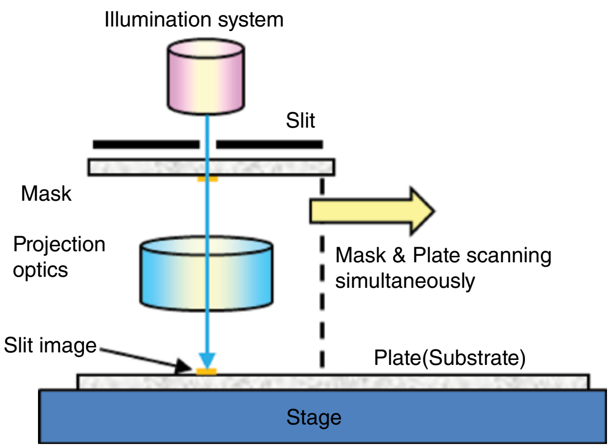


Figure 13.7 Concept of scanning exposure system.

low. With the demand for larger screen sizes as well as increase in sizes of the glass substrates, it is necessary to develop exposure systems with larger projection optics and lithography system for higher throughput. Thus, the projection scanning exposure system was devised to replace the stepper exposure system.

The concept of the projection scanning exposure is shown Figure 13.7, and the exposure procedure for a Gen 7 size substrate (1,850 × 2,200 mm) with six-up panelization of 47-inch diagonal panels is also shown in Figure 13.8. The UV light from the light source is irradiated onto a mask (850 × 1,200 mm) through the circular arc or linear slit with a narrow aperture as long the width the mask. The mask image with the slit shape is projected onto the substrate and 1:1 aperture image is exposed. During exposure, the mask and the substrate are synchronously scanned toward the end of the panel region. This scanning system can expose the whole area of a single display panel (area = exposure width by scan distance) without any visible seam. Subsequently, the system is stepped to the next display panel. By such step and repeat motion, the entire substrate can be exposed, as shown in Figure 13.8. In this example, the Gen 7 size plate is exposed by six scans. The feature of this system is to realize large-area exposure with a resolution as high as 3 μm. With high-precision measurement systems and adjusting mechanism of projection optics, it is possible to achieve 0.5 μm overlay accuracy and satisfy the requirement for TFT array patterns.

The details of scanning exposure systems using the mirror projection or the multi-lens projection are discussed in the following section.

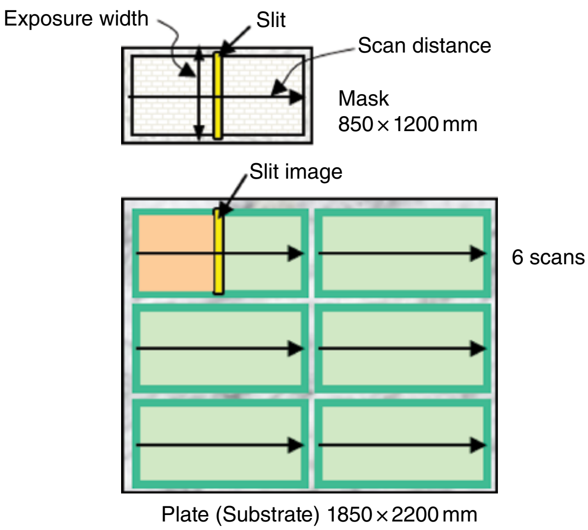


Figure 13.8 Example of Gen 7 47-inch panel by six-shot exposure.

13.4.5 Mirror Projection Scan System (Canon)

The Canon mirror projection aligner is a projection scan exposure system with mirror projection optics. The reflective optical systems using mirrors have simpler components than transparent optical systems using lenses, providing such benefits as no chromatic aberration and degradation in image performance. The optics consisting of the concave and convex mirror has an advantageous feature that high-quality image areas with arc shapes, which is cut out from the circular belt zone along the inner circumference on the concave mirror in order to minimize the distortion error, can be easily obtained. The slit mask image made from the arc-shape slit is projected onto the plate. That system can achieve the large area exposure with high resolution.

Figure 13.9 shows the conceptual diagram of the mirror projection aligner. Its optics consists of the trapezoidal, concave, and convex mirrors. The large concave mirror, having a large diameter to allow exposing a large panel seamlessly in a single pass with a wide enough exposure area, enables a significant increase in throughput and overall productivity.

As an example, the specifications of Gen 6 size and Gen 8 size mirror projection aligners by Canon are summarized in Table 13.3, and a photo of the Gen 6 size Canon mirror projection aligner MPAsp-E813H is shown in Figure 13.10.

13.4.6 Multi-Lens Projection System (Nikon)

13.4.6.1 Multi-Lens Optics

Figure 13.11 shows the principle of the multi-lens optics. The high resolution property of each projection lens is maintained across the entire image field, with this two-row lens array arrangement allowing for exposure with 2–3 μm high resolution. This lens array precisely works as the giant lens with the same NA that each small lens has, and it offers such an advantage that the increase in the number of the projection lens on the array can easily scale up the capability for glass substrates with further increased sizes. In fact, the Gen 10 size system (Nikon FX-101S) utilizes a 14-lens array for exposing in one scan displays panels over 60 inches in size.

13.4.6.2 Multi-Lens Projection System

Figure 13.12 shows the configuration of the exposure system with a multi-lens optical system.

The bending of the large-sized photomask is compensated by the focusing mechanism. Less than 0.5 μm overlay accuracy is achieved by the alignment sensors and simultaneous measurement systems.

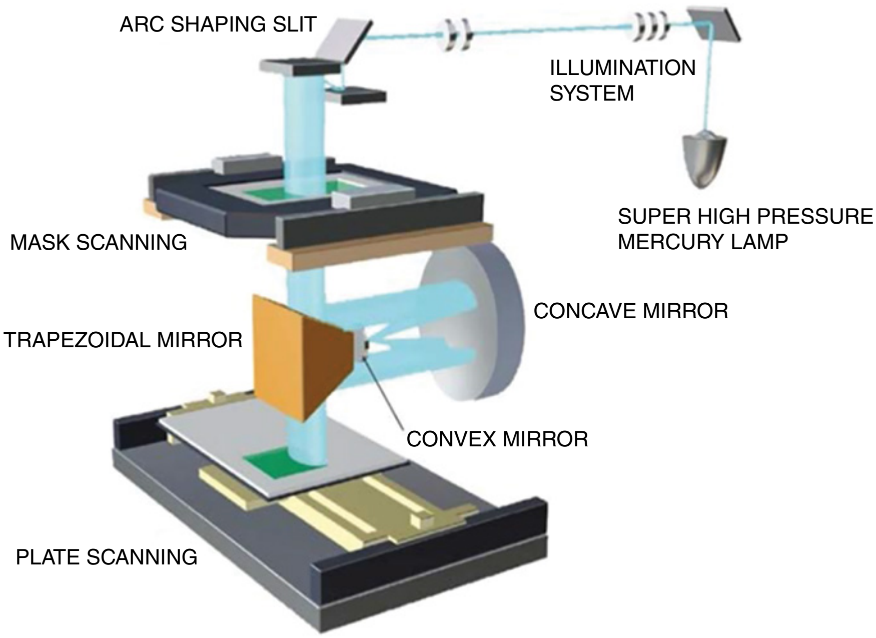


Figure 13.9 Conceptual diagram of mirror projection optical system (*Source:* Courtesy of Canon).

Table 13.3 Specifications of MPAsp-E813H (Gen 6 size) and MPAsp-H803T (Gen 8 size) mirror projection scan systems.

	3MPAsp-E813H	MPAsp-H803T
Generation	G6	G8
Exposure System	Mirror: 1:1	Mirror: 1:1
Mask Size	850 mm × 1,200 mm	850 mm × 1,400 mm
Plate Size	1,500 mm × 1,850 mm	2,200 mm × 2,500 mm
Resolution	1.5 µmL/S	2.0 µmL/S
Application	High-resolution small-medium LCD&OLED panels	High-resolution large LCD&OLED TV panels (e.g. UHD)

(*Source:* Courtesy of Canon)

The specification of Nikon FX-86SH2 for G8 is summarized in Table 13.4, and its exterior view is shown in Figure 13.13.

13.4.7 Proximity Exposure

In the proximity exposure system, the photomask plate and photoresist-coated substrate are placed in parallel with a very narrow gap (proximity positioning), and then a collimated UV beam is illuminated through the photomask so that the mask image is transferred to the photoresist layer. The image size of the photomask and that formed on the glass plate are exactly the same. Using a close contact between substrate and photomask in a contact exposure system can facilitate high image resolving capability and avoid diffractive scattering light. However, the photoresist and photomask are vulnerable to damages caused by small particles or

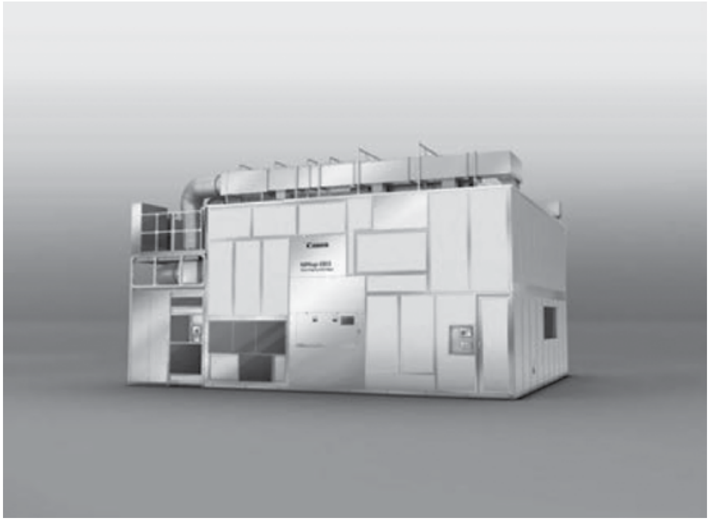


Figure 13.10 Exterior view of a Gen 6 size mirror projection scan system, Canon MPAsp-E813H (*Source:* Courtesy of Canon).

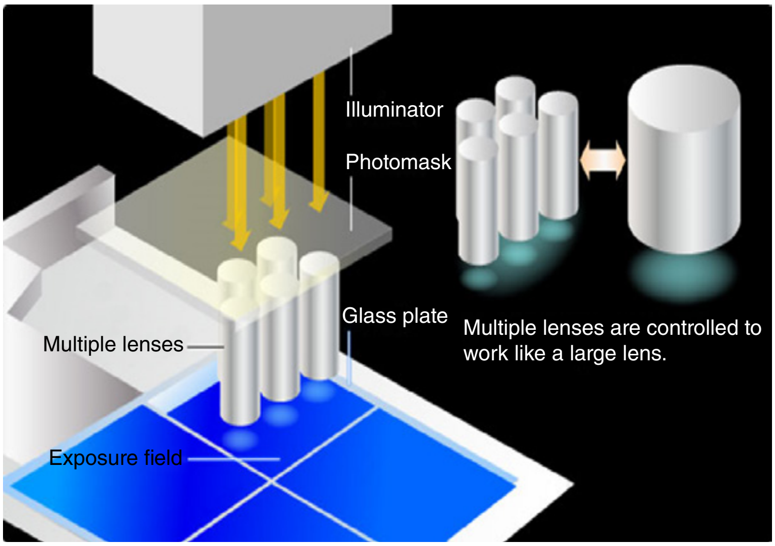


Figure 13.11 Principle of multi-lens optics (*Source:* Courtesy of Nikon).

dust on the substrate. Thus, only proximity systems were introduced for large-sized exposure, despite the slight degradation of the resolving capability.

Figure 13.14 shows the conceptual architecture of a proximity exposure system. The UV light beam from a Hg lamp source passes through Mirror 1, fly-eye lens, and collimation mirror to form a parallel beam. That beam irradiates the photoresist coating by passing through a photomask placed in proximity of the glass substrate surface. For large-sized substrates with multiple display panels, the stage is stepped in (x,y) directions for multiple shots, as shown in Figure 13.15. The resolution in such systems is defined by the source collimation quality and the proximity gap. Typical performance-results for proximity exposure systems using ~100 μm proximity gap are: (1) proximity gap accuracy: ±10 μm, (2) resolution: ~8 μm, (3) alignment accuracy (overlay): ±1.0 μm, and (4) total pitch accuracy: ±3.0 μm.

Proximity exposure systems are typically used for BM (black matrix), RGB color layers, photo spacers, and VA rib fabrication, which are relatively low-resolution patterns.

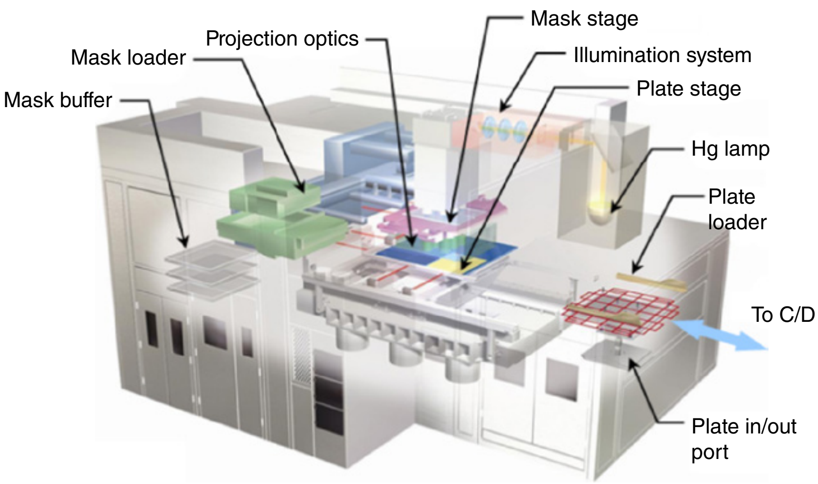


Figure 13.12 Exposure configuration with multi-lens optical system (*Source:* Courtesy of Nikon).

Table 13.4 Specifications of multi-lens projection system, Nikon FX-86SH2.

FX-86SH2 Performance	
Resolution (L/S)	2.2 μm (g+h+l–line)
Projection magnification	1:1
Alignment accuracy	≦ 0.5 μm)
Max. plate size	2,200 mm × 2,500 mm
Takt time	49 sec./plate Conditions: 2,200 mm × 2,500 mm, 4 scans, g+h+l-line, 30 mJ/cm^2

(*Source:* Courtesy of Nikon)

Figure 13.13 Exterior view of multi-lens projection system, Nikon FX-86SH2 (*Source:* Courtesy of Nikon).

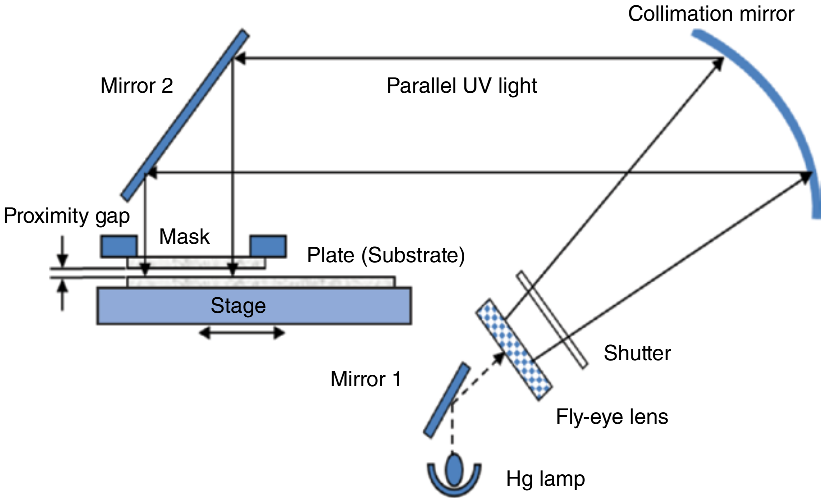


Figure 13.14 Diagram of a typical proximity exposure system.

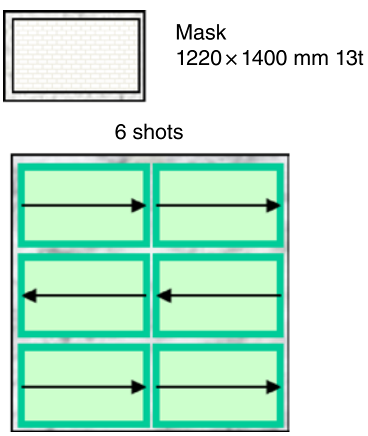


Figure 13.15 Example of Gen 8 size substrate, with six shots panelization.

13.5 PHOTORESIST DEVELOPMENT

In the development process, the latent image formed by UV exposure in the photoresist layer is converted into a physical pattern as portions of the photoresist material are dissolved in the development chemical solution (developer). The development process consists of (1) development, (2) deionized water (DIW) rinse, (3) dry, and (4) post-bake, as shown in Figure 13.16.

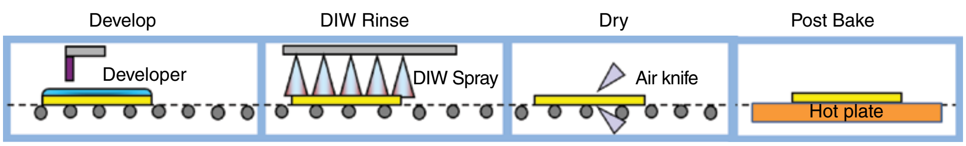


Figure 13.16 Schematic of developing process flow.

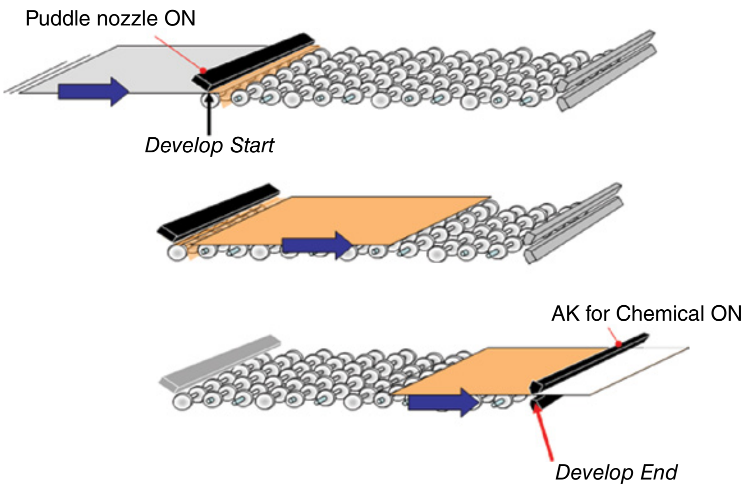


Figure 13.17 Principle of puddle development equipment operation: the substrate moves inline on rollers and a linear nozzle dispenses developer solution. An air knife (AK) is used to remove the developed resist solution (*Source:* Courtesy of Screen Finetech Solutions).

There are three main approaches for applying developer solution onto a PR coated substrate during the development process: liquid shower (spray), dipping, and puddle. The puddle method can achieve high development uniformity even for large-sized substrates, and it is mostly employed for substrate sizes over 5G. The puddle development method utilizes a thin liquid layer of developer solution that is dispensed on the PR layer through a slit nozzle. In general, the puddle development method is considered the best approach in terms of uniformity.

The principle of the puddle development is shown in Figure 13.17. The development process begins when the substrate moves just beneath the puddle nozzle where the developer solution is dispensed onto the glass substrate. The development process continues while the substrate travels in-line through the equipment until the substrate reaches the AK (air knife) position and the solution is blown away completing the process. As a puddle nozzle with similar width as the substrate is used, a highly uniformity can be achieved even for the large-sized substrates. Compared to other methods such as shower and dipping, puddle process can significantly minimize the consumption of development chemicals. Furthermore, the running cost can be reduced even more by recirculating the developer solution and controlling the concentration of the chemical during the recycling procedure. For example, aqueous TMAH (tetra-methyl ammonium hydroxide) solution of typically 2.38% concentration is used as the development chemical for positive photoresist.

The developed substrate is then post-baked at temperatures typically between 120 to 180 °C on a hot plate or in an oven chamber. The post-bake procedure solidifies the remaining photoresist to increase its durability for the subsequent process, such as wet etching, dry etching, or ion implantation. In some cases, UV curing is additionally applied to obtain harder layers.

13.6 INLINE PHOTOLITHOGRAPHY PROCESSING EQUIPMENT

In a typical manufacturing process, all steps for substrate pre-cleaning, dehydration bake, photoresist coating, pre-bake, exposure, and post-bake are performed in an integrated system in which the unit process stations are connected together so that the substrate can be continuously and sequentially processed in a single flowing line. The typical structure of an inline system is shown in Figure 13.18. Substrates are loaded into the loader unit, and then is move sequentially through the cleaner, dehydration bake, photoresist coater, and pre-bake stations stations. After exposure, the substrate is moved back through developer and post-bake stations, and finally unloaded. In some cases, an AOI (automatic optical inspection) station is included after post-bake. The substrate transportation is achieved by robotic arms. Since each station is designed to have the

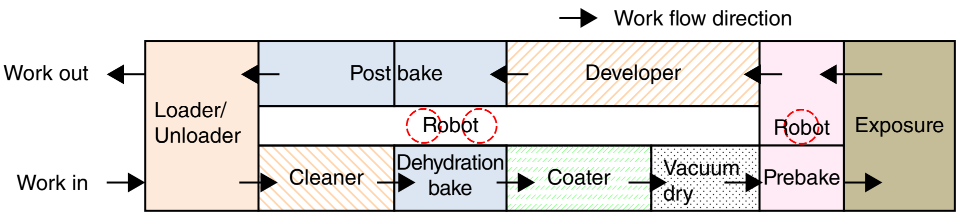


Figure 13.18 Schematic diagram of inline photolithography system (*Source:* Courtesy of Screen Finetech Solutions).

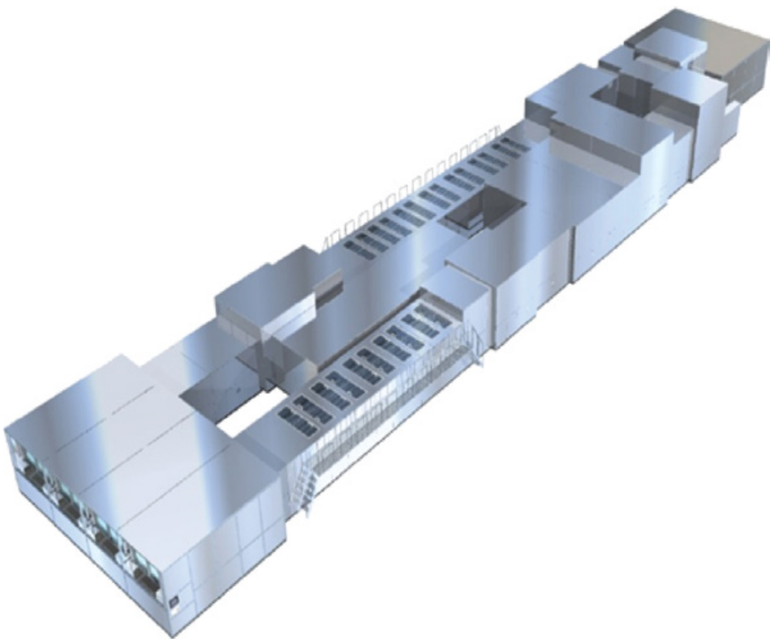


Figure 13.19 Exterior view of a Gen 8 size inline photolithography system (*Source:* Courtesy of Screen Finetech Solutions).

same cycle time, the inline system is quite efficient in terms of footprint and throughput. Figure 13.19 shows the exterior view of a Gen 8 size inline photolithography system provided by Screen Finetech Solutions.

13.7 PHOTORESIST STRIPPING

After etching or ion doping through the patterned photoresist mask, the photoresist material is removed with the help of a chemical solution (wet removing) or with a combination of dry (plasma/ashing) and wet processes.

As the surface of a photoresist coating can become carbonized or hardened during use as mask for etching or ion doping, it can be difficult to strip the photoresist by wet processes alone. Therefore, O_2 ashing is employed to remove the carbonized and hardened photoresist. Once this surface layer is removed, the remaining photoresist material can be removed and cleaned by wet processes. Table 13.5 shows etching processes and stripping methods for a-Si TFT and LTPS.

Usually O_2 ashing is achieved using the same equipment as that used for dry etching, where O_2 plasma is excited in the dry etching chamber for PR removal. The equipment for wet removing is similar to that for a

Table 13.5 Photoresist removal processes for a-Si and LTPS TFT.

		a-Si TFT		LTPS	
layer	material	process	PR removal	etching	PR removal
Channel S/D	a-Si n+Si Poly-Si	Dry	O_2 ashing + Wet	Dry	O_2 ashing + Wet
Gate electrode	Mo/Al Cu/Mo	Wet	Wet removal	Wet Dry	Wet removal O_2 ashing +Wet
Contact hole	SiN SiO_2	Dry	O_2 ashing + Wet	Dry Wet	O_2 ashing +Wet Wet removal
S/D	P+ B+ Doping	-	-	Ion Dope	O_2 ashing + Wet
Pixel	ITO	Wet	Wet removal	Wet	Wet removal

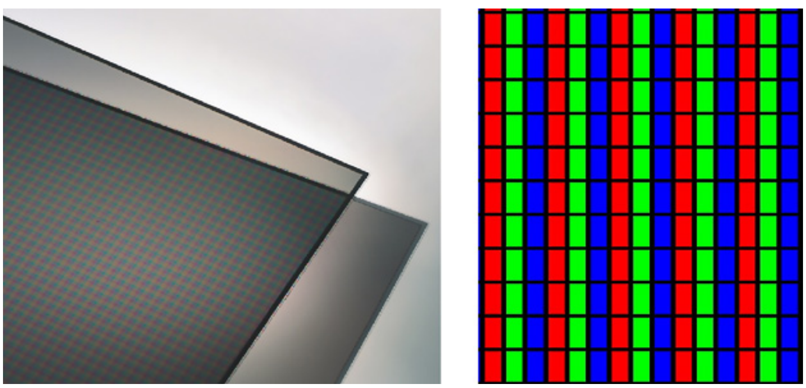
wet etching process. It consists of shower (spray) removing, rinse, post cleaning, and drying zones, typically with a tilted substrate to help removing chemical and water.

13.8 PHOTOLITHOGRAPHY FOR COLOR FILTERS

Manufacturing of CF plates has evolved with that of TFT arrays by concomitantly adapting to the increase of glass substrate sizes and the scale of production equipment so that the two substrates can be successfully coupled for filling the thin liquid crystal layers. As the patterns of BM (black matrix) and RGB (red, green, and blue) layers are prepared by photolithography, photo-sensitive materials based on photoresists with pigment particles dispersed within are used for patterning these layers. CF manufacturing has remarkably advanced with the increase in the size of glass substrate for TFT arrays, starting with G1 size (320 × 400 mm) in the mid-1980s and gradually going up to Gen 10 size (2,880 × 3,130 mm) as result of progress in production equipment and manufacturing technology.

13.8.1 Color Filter Structures

A photo of two overlapping color filter plates is shown in Figure 13.20(a). In this photo, the Moiré interference color pattern can be observed in the overlapping area. Figure 13.20(b) shows a magnified image in which the



(a) (b)

Figure 13.20 (a) Photograph of two color filter plates showing Moiré pattern in the overlap area, (b) RGB pixel arrangement on the color filter array.

RGB color layers are patterned in the pixel area including the black matrix (BM) pattern that blocks the undesired light between color pixels and shields the TFT being placed between the color layers.

The fundamental function of a color filter is to provide color images on the display screen. The essential structure of a color filter consists of RGB primary color cells and the black matrix (BM), which separates each RGB cell to prevent mixing of RGB colors and prevents undesired light leaking from the backlight. While the basic structure and function of BM and RGB patterns are similar in different liquid crystal display modes (i.e., TN (twisted-nematic) [1], VA (vertical alignment) [2], and IPS (in-plane switching) [3]), the detailed structure of the color filters array varies in each liquid crystal mode.

13.8.1.1 TN

TN is the original mode created for LCDs, and still offers the most modular basics for color TFT-LCDs. Figure 13.21 shows the CF structure for TN mode, which also represents the initial and conventional architecture for CF array. The BM layer blocks the light passing through areas between the pixels where the LC orientation is not controllable, in order to enhance the contrast ratio. To avoid undesired reflection at the panel surface, BM must be a low-reflection component. To electrically control the liquid crystal molecules, transparent conductive films based on ITO (indium-tin-oxide) are deposited across the color filter area.

The pixel sizes for recent high-end display models are 230 μm for 60-inch 4k (3,840 × 2,160 mm) TVs, and 50 μm for 5.5-inch mobile phones with WQHD (2,560 × 1,440 mm) resolution. Typically, the color layers are 1.5–2.5 μm thick and black matrix layers are 1.0–1.5 μm thick. In general, RGB patterns are overlapped with the black matrix layers by a few μm to avoid color degradation by light leakage.

13.8.1.2 VA

The vertical alignment (VA) mode was created to improve the viewing angle properties. In TN mode, liquid crystal molecules are horizontally aligned with respect to the glass substrate, but in VA mode the nematic molecules are vertically aligned by the unique protrusion structure. The color filter structure for VA cell is shown in Figure 13.22.

Usually the protrusion (VA pattern or "VA Rib") is formed on the ITO layer, where the LC molecules are aligned along the vertical direction and can be driven to the oblique directions by the application of an electrical filed. The VA pixel is divided into four domains resulting in negligibly small viewing angle dependency. The "VA Rib" is also prepared by photolithography.

13.8.1.3 IPS

Another LC mode that offers wider viewing angle is IPS (IPS is a registered trademark of Japan Display Inc). In IPS mode, two counter electrodes are formed on the TFT substrate and switching is achieved by the

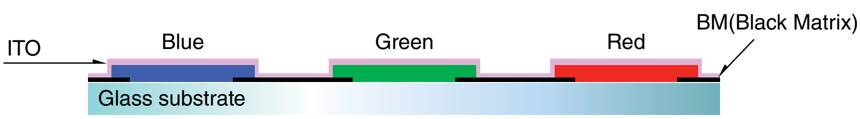


Figure 13.21 Color filter structure for TN mode.

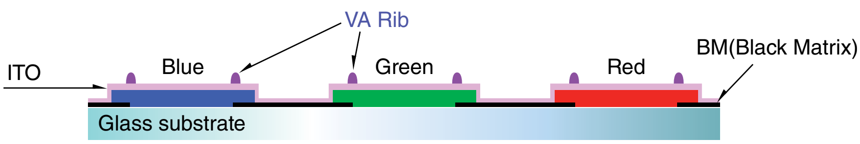


Figure 13.22 Color filter structure for VA.

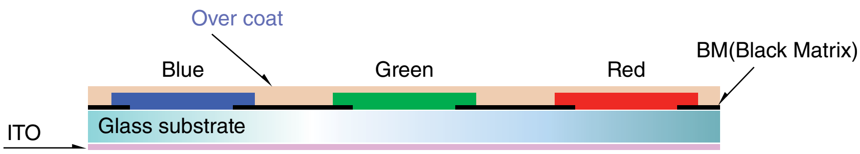


Figure 13.23 Color filter structure for IPS.

rotation of the liquid crystal molecules. Thus, an ITO electrode is not required on the CF array since the molecules are controlled by the laterally structured electrodes on TFT plate (Figure 13.23). However, an overcoat layer passivating the CF array becomes indispensable for meeting stricter requirements for surface flatness to eliminate orientation defects of LC molecules and for preventing impurity diffusion from color layers into the LC layer.

13.8.2 Materials for Color Filters

The main materials used for color filters are: (1) black matrix, (2) RGB color materials, and (3) photo spacers (PS) materials. The properties of those materials are described below in this section.

13.8.2.1 Black Matrix Materials

The main function of BM is to block unnecessary light from the backlight. One of the critical properties of BM is black density, which is defined as OD (optical density) value. So far, two types of BM materials are available, based on metal and resin.

The metal type BM consists of double or triple layers formed by Cr and its oxide [4]. The metal type BM features higher OD value, which can reach as high as over 3.5 for a < 0.2-μm-thick BM layer. However the metal type BM is not in use anymore due to environmental protection regulations.

For the latest color filters, the resin-type BM is dominantly used. Recently, the improved resin-type BM materials offer high OD value, high volume resistivity, better adhesion, and low reflection. Especially in IPS mode, BM must have high enough electrical resistance to avoid any impact on the molecular alignment. Adhesion to the glass is also important to prevent any failures caused by detached resin during or after the cell process. Low reflectance is another key requirement for the LCD panel to increase visibility, as reflection by BM may create image degradation under constant exposure to ambient conditions.

Typical OD value and volume resistivity are shown in Table 13.6. It should be remarked that, in general, materials with higher OD tend to show lower resistivity. The BM material is the resin (photoresist) containing carbon particles, and its properties can be controlled by the surface structure and size of the carbon particles. For the small/middle size mobile displays using IPS, BM with high resistance (over 10^{10} cm-Ω) and low reflectance (less than 2%) is required. Those mobile applications also require high-adhesion BM to keep good enough shock-proof property.

13.8.2.2 RGB Color Materials

The property of the color filter mainly depends on the RGB color materials and their optical properties. The RGB color layers are formed by the photoresist (or color resist) within which color pigment particles are

Table 13.6 Properties of resin-type BM.

	High Resistive Material	Low Resistive Material	Remark
OD Value (/mm)	**2.4 ~ 3.7**	**3.0 ~ 4.5**	
Resistivity (cm-W)	**10^{10} ~ 10^{15}**	**10^{6} ~ 10^{9}**	**DC1V**

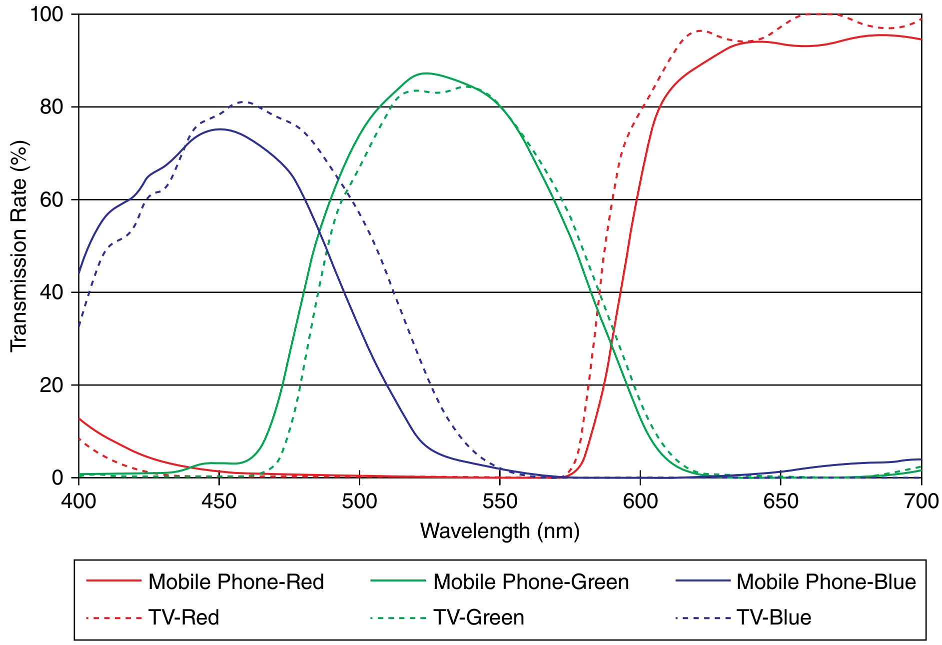


Figure 13.24 Transmission properties of RGB color layers.

dispersed. The key functions of those color resists are to realize the high-quality image with high brightness and contrast ratio on the LCD panel. The color resist is required to achieve high transmission and color purity, which are opposing properties.

A typical color resist consists of RGB materials dispersed into a negative type photoresist. The pigment type RGB materials used to be the major color materials. Due to the requirements for higher chromaticity and transmission, the dye or dye/pigment mixture type RGB materials have become the most advanced materials with improved temperature durability of the dyes.

Figure 13.24 shows the typical color transmission properties for RGB color layers. Both TV and mobile applications basically use the same color photoresist.

Recently "high contrast" and "high-color purity" versions with respect to the "standard" version have been developed. High-color purity version offers larger NTSC area ratio in chromaticity diagram shown in Figure 13.25. A "super high color purity" version, which satisfies EBU requirements, has recently become available. Besides those TV requirements, recent mobile phone applications strongly demand higher transmission and color purity for higher image quality and brightness performance.

13.8.2.3 PS (Photo Spacer) Materials

PS is a material patterned to form spacers ~3 μm in height to maintain a uniform gap between TFT and color filter glass substrates where the liquid crystal is filled. The gap is very important to achieve sufficient uniform optical properties of the liquid crystal layer. Therefore, PS height variation must be controlled to be less than 0.1 μm over the entire substrate. Otherwise, LC cell thickness cannot be precisely controlled and may also result in leakage of the LC material or air intrusion into the cell. Furthermore, PS material is required to have proper elasticity to compensate the expansion and shrinkage of the LC layer caused by temperature changes and the stress forces applied from the outside of the display panel.

To keep the uniform cell space over the entire cell area, typical PS materials used are negative type photoresist based on acrylic resins with suitable elasticity and mechanical strength.

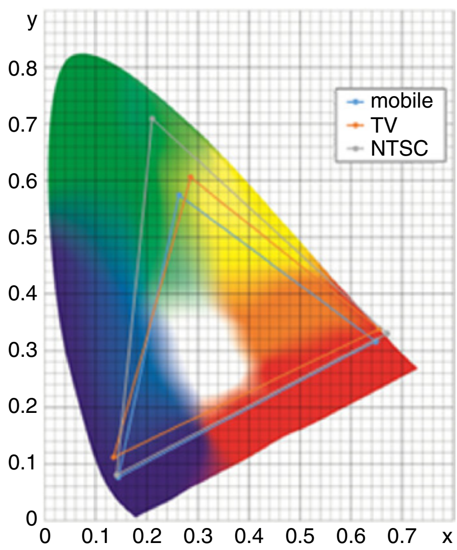


Figure 13.25 Color properties in chromaticity diagram.

13.8.3 Photolithography Process for Color Filters

Various methods, such as inkjet, printing, and electro-deposition [5], have been used for fabricating color filters in the past. Today, the dominant color filter fabrication method employed in manufacturing plants is the photolithography process by utilizing photoresist containing dispersed color pigments [6].

The color filter plates used to be provided by color filter vendors from their sites to TFT manufacturers. However, with the increase in the glass substrate sizes, color filters are now being made on-site in TFT manufactures' plants.

The color filter manufacturing process is shown in Figure 13.26. As can be seen in the figure, after the BM layer is formed, the R, G and B color layers are subsequently fabricated. Then, the ITO layer or overcoat is applied to the top surface. As an additional process, the VA Rib or PS is formed for specific applications. For the patterning processes of BM, R, G, B, PS and VA, the microfabrication technology based on "photolithography method" is applied, which consists of color resist coating, exposure, development and color resist post-bake, as shown in Figure 13.26(b).

13.8.3.1 Color Resist Coating

After cleaning of the glass surface, the color resist is coated (typical thickness: 1.0–1.5 μm). In order to keep sufficient uniformity in thickness, "spin coating," the conventionally developed method, used to be frequently applied. With the increase of the glass substrate size up to 6G or over, slit die coating [7] has become the commonly applied method.

After coating, the color resist is dried under reduced pressure and pre-baked to harden the layer to endure the processes that follow.

13.8.3.2 Exposure

After color resist coating, photo-exposure is applied to form the precise and accurate patterns. Usually, the negative-type color resist is used. Exposure is performed using the proximity exposure system by UV light (see section 13.4.7). Upon exposure to UV light, the exposed area of the negative-type color resist can undergo photochemical reactions to form the patterns to be remained on the glass substrate. For Gen 8 to Gen 10 glass sizes, "step and repeat" exposure, in which the photomask is moved by step motion with a precise alignment between the photomask and substrate at each step, is used.

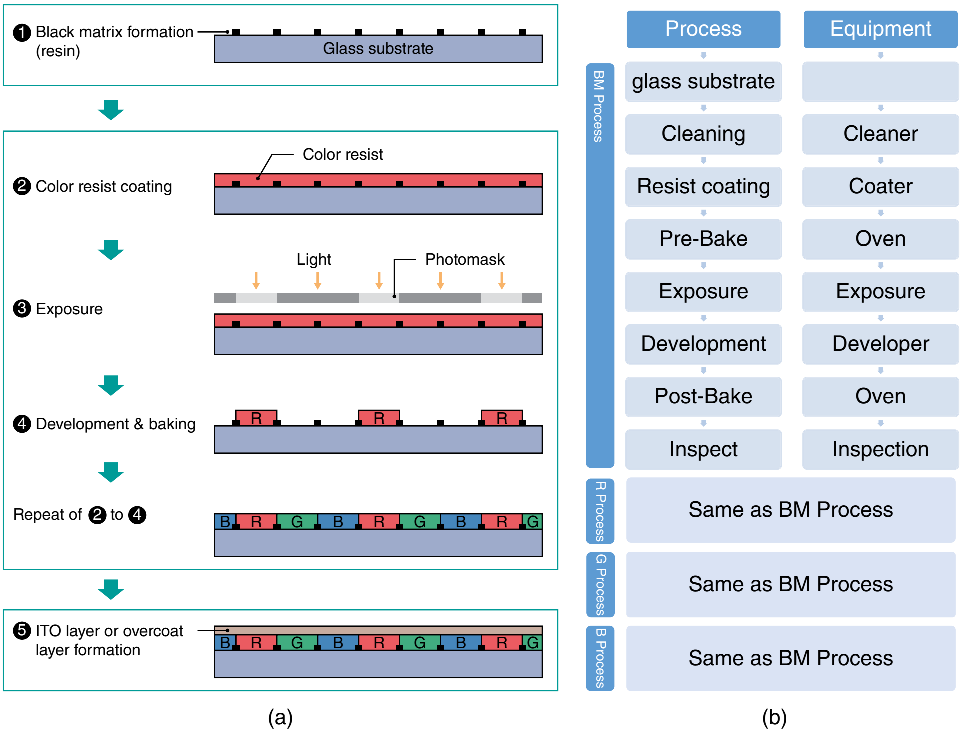


Figure 13.26 (a) Color filter device fabrication process and (b) flow chart.

13.8.3.3 Development

The color resist in the unexposed area is removed by spray shower of alkali-type development chemical solution. After the residual solution on the substrate is washed away with deionized water, the color resist on the substrate is post-baked in the oven.

Fabrication of BM and RGB patterns are repetitively performed by the same processing steps. The BM layer is prepared first and then the RGB layers are subsequently formed by precise error-minimizing alignment with the BM patterns.

The equipment for completing those coating, exposure, and development processes is similar to that for TFT-array production. Each process station is designated as a specific inline setting, which can minimize substrate handling and the footprint of equipment. Figure 13.27 shows the conceptual layout for color filter manufacturing in the cleanroom. Each dedicated line handles the BM, R, G, or B layer fabrication process. Such equipment is similar to that for TFT array photolithography process. BM and RGB lines are connected by the automatic cassette transportation system. After the cassette is loaded into the entrance of the BM station, a single plate is moved to the cleaner, the resist coater, and the pre-bake station by the robotic handler, and then exposure is carried out. After the exposure process, development and post-baking are applied, and then optical inspection is done. Those processes are automatically and precisely controlled to promote defect-free manufacturing quality. As an alternative layout, the complete inline structure, in which the BM and RGB lines are connected in-line and the glass substrates and cassettes are transported to one direction, is available.

The overcoat or PS layers are formed using the same photolithography technique as that for the color resist. Materials for the overcoat have two curing types, that is, light curing and thermal curing. In the fabrication process by using the light curing materials, the photoresist for the overcoat is coated over the color layer, followed by low-pressure drying, pre-baking, exposure, development, and post-baking procedures. In the case

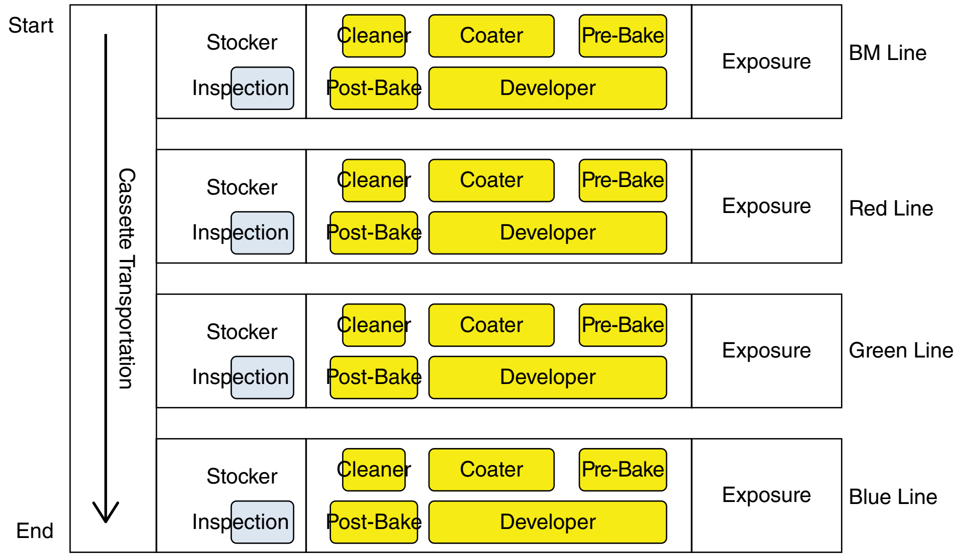


Figure 13.27 Conceptual layout of color filter manufacturing line.

of using thermal curing type overcoat materials, exposure and development procedures are not available. The PS is formed by the same procedures using the light curing type overcoat materials.

13.8.4 Higher-Performance Color Filters

13.8.4.1 Mobile Applications

Mobile applications, typically represented by smartphones, require high pixel density to display picture-like images on the panels. Presently, 300 ppi (pixel-per-inch) is the most common pixel density for mobile applications, and 400-450 ppi will dominate in the near future. In the further future, up to 600 ppi may be required.

As higher pixel density is expected for mobile displays, color filters with narrower and thinner BM patterns are required. For high density pixels, the aperture ratio, which is the ratio of the opening area to the total pixel area, may become smaller and smaller. The aperture ratio is directly related to the transmission efficiency of the backlight, which modulates the brightness of displays. When the pixel density is enhanced up to 600 ppi, the aperture ratio becomes so small that the brightness significantly goes down. Therefore in the high-density pixel arrangement, it is necessary to decrease the stripe width of the BM to utilize the most of the backlight. Presently, the width of BM is over 5 μm. For 450 ppi and 600 ppi density, the stripe width of the BM should be reduced to around 4 μm and 3 μm, respectively. To meet the technical requirements, the development of new BM materials with the smaller thickness keeping the same OD value is desired. Besides, PS materials will become so narrow that similar issues must be resolved for PS as well.

13.8.4.2 TV Applications

With the infrastructure development for higher definition image broadcasting, LCD panels for TV applications are also moving along that development toward higher quality images with higher color reproducibility. Recently, the backlight generated by narrow spectrum LED light sources and quantum-dot LEDs [8] for each RGB color has been developed.

To better fulfil such requirements, fundamental properties of color materials must be improved. The ideal color filter is required to exhibit both higher brightness and high color purity, but brightness (light transmission) and color purity are properties of conflicting nature. In order to resolve that issue, 100% dye materials, instead of the conventionally used hybrid materials based on the mixture of pigments and dyes, are recently evaluated for improving the color performance. Though, in general, dyes are more vulnerable than pigments to degradation induced by light and temperature, the development of highly durable 100% dye materials would be the key to open up future TV applications.

References

1 M. Schadt,W. Helfrich, Voltage-dependent optical activity of a twisted nematic liquid crystal, Appl. Phys. Lett. 18, 127 (1971).
2 A. Takeda, et al., A super-high-image-quality multi-domain vertical alignment LCD by new rubbing-less technology, Digest SID Symposium, 98, p. 1077 (1998).
3 M. Oh-e, et al., Principles and characteristics of electro-optical behaviour with in-plane switching mode, Proc. of the 15th International Display Research Conference (Asia Display 95), p. 577 (1997).
4 M. Bender, et al., Economically sputtered black matrix systems for FPD applications, Digest 1996 Display Manufacturing Technology Conference, p. 71 (1996).
5 A. Matsumura, et al., The new process for preparing multicolor filter for LCDs, Proc. Eurodisplayb'90, p. 240 (1990).
6 T. Sugiura, Development of pigment-dispersed-type color filters for LCDs, Journal of SID, 1/3, p. 341 (1993).
7 D. Schurig, et al., High performance capillary coating system, Digest 1994 Display Manufacturing Technology Conference, p. 99 (1994).
8 H. Ishino, et al., Novel wide-color-gamut led backlight for 4k LCD embedded with mixing cup structure for isotropic light source, Digest SID Symposium 2014, p. 241 (2014).