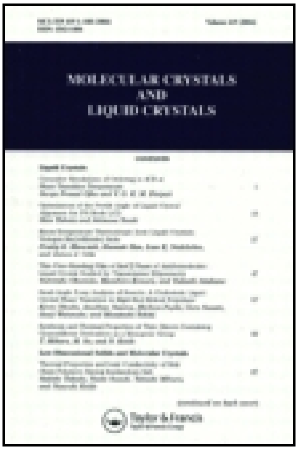

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Flexible Display Technology - Opportunity and Challenges to New Business Application

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Flexible Display Technology – Opportunity and Challenges to New Business Application

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Flexible displays have attracted much attention because they will be the key to open the next generation display market in the ubiquitous era. Many progressive prototypes of the flexible e-papers and the flexible AMOLEDs enable to have expectation that the early product of the flexible display will come into the market in the near future. In addition, it is expected that the remarkable development of the printing technologies and the organic electronics can realize the rollable, extremely low price, and even disposable displays. In this paper, the prospect of the flexible display, the technical issues, and the R&D status are briefly reviewed.

Keywords: flexible AMOLED; flexible display; flexible e-paper; organic electronics; printing technology

I. INTRODUCTION

Rapid growth of computer and network technology makes computer and electronic information systems come into wide use not only at office but also at home, and technology development of processing and storing a considerable amount of information inside a small computer chip allows these electronic devices to be compact, portable, and slim with multimedia functions. Displays, as a tool for visually communicating data and information through these electronic devices, recently have been required in the direction of being portable, thin, lightweight, and conformal as well. Thus, there has been an enormous attraction for flexible displays that meets the customer or market requirements [1]. Flexible display is expected to be used for mobile products adopting small & medium size display such as a cell-phone, PDA, and MP3 player due to its light-weight and durable properties.

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And, with creating the areas that were limited or impossible to apply conventional flat panel display based on glass substrate, flexible display will open new applications of portable IT products with highly portable and rollable properties such as e-book or e-paper, ending up with replacing current printed publications like newspaper, magazine, textbook, cartoon and etc. Besides, it is possible to extend the applications for wearable display owing to its durable and fully conformal characteristics as well as to create new demands for indoor or outdoor information display. Advanced flexible technologies in the near future allow us to reduce cost substantially through Roll-to-Roll processing [2–4], for example, resulting in speeding up the appearance of new concept display such as rollable display, blind type TVs set on ceiling or new displays formed on window of cars and building. In this paper, we briefly review the flexible display prospect in terms of technology trend and business opportunity, and then discuss development status along with LGD's flexible display technology.

II. FLEXIBLE DISPLAY PROSPECT

Since Cathode Ray Tube called as the 1st generation display was used for last 30 years above just for enjoyment and simple information delivery with good image quality, flat panel displays such as LCD and PDD as the 2nd generation display have replaced the CRT due to its space saving, thin and light, large in size properties along with interactive information, resulting in producing wall hanging type display or portable display. In addition, these flat panel displays have been used for new applications such as a mobile phone and information display. However, there are limited features on design flexibility, realistic image reproduction, and digital convergence. Thus, future display as the 3rd display including flexible display and 3-dimensional displays will be main stream in the future ubiquitous and convergence era with clean and green technology. Especially, flexile displays have been attracted enormously because of its design flexibility, portability, and more space saving features, which meet consumer requirements such as durability, portability, and conformal rugged direct viewing image of the new display product.

When the flexible display was first developed several years ago, it was a small-size prototype just for a mobile phone and an e-paper with slightly bendable and lower power consumption characteristics. As time goes by, technology development in terms of the flexible substrate, active device, mode, and flexible process has been made in many ways, resulting in emerging several prototype samples of the flexible e-papers and the flexible AMOLEDs. Thereafter, many progressive prototypes that have a good flexibility in some way with a larger size than before have been developed continuously. From a technological trend's point of view, it will be possible to develop flexible displays that have a high quality image, completely conformable or even disposable property with very large size in the future, ending up with creating many new applications such as billboard, wall display, roll-up display, and so on. Figure 1 shows flexible display trend in terms of development direction.

Flexible display market is expected as prospective future display with rapid growth for EPD, LCD, and AMOLED according to i-Supply research published on 2008 [5]. For the case of EPD, the market size will be grown fast from \$80 million on 2007 to \$2772 millions up to 2013, and flexible EPD product will be a main product with market portion of 80% above as appeared in Figure 2.

There are lots of business opportunities for the flexible display products by integrating with ubiquitous, wireless network, and digital convergence technology. We can classify future display products simply into two categories: bendable display such as e-book, e-paper, bendable GPS, curved mobile products, and rollable display such as rollable e-paper, rollable PC, Billboard, Roll-up TV. Thus, future converging technology enables us to use flexible displays anywhere, any time with multimedia functions.

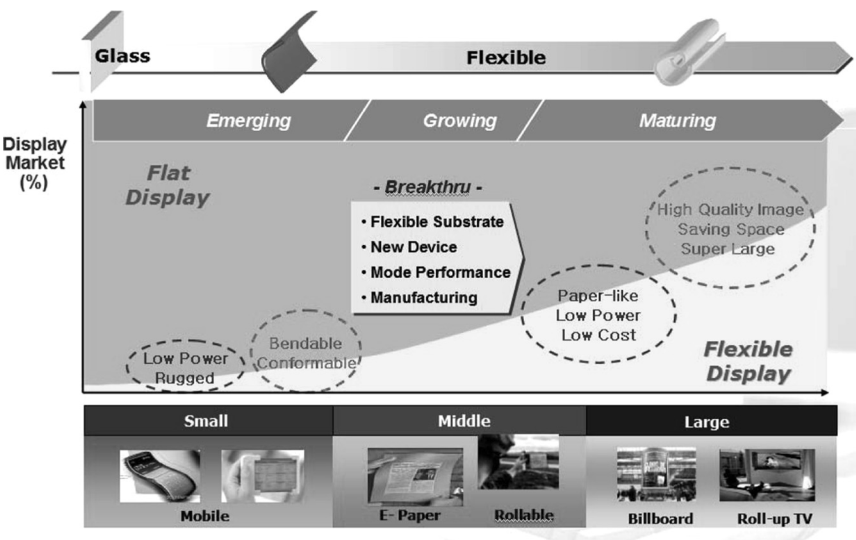


FIGURE 1 Flexible display trend: direction.

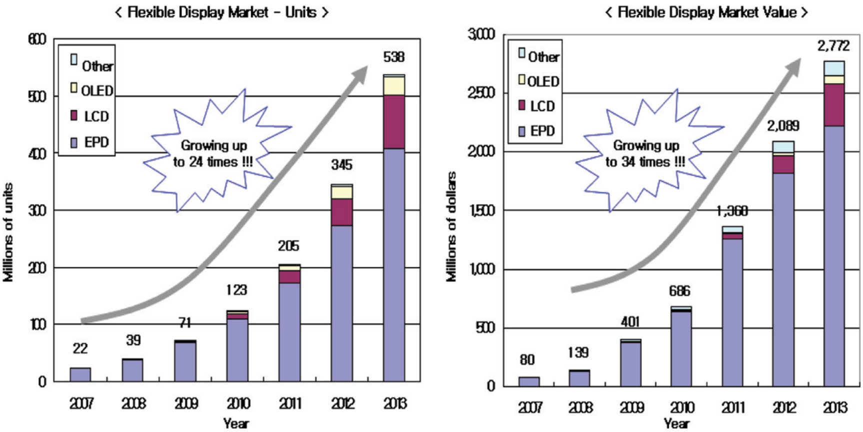


FIGURE 2 Flexible display Market forecast by i-supply, 2008.

III. FLEXIBLE TECHNOLOGY STATUS

Although the prototypes of flexible transmitive type LCDs have been developed by LGD, SSE, Sharp, Toshiba, Hitachi from 2002, technologies for flexible reflective-type EPDs and self-emissive type AMOLEDs have been developed and kept being improved much more than other display modes by LGD, SSE, Epson, Fujitsu, Plastic Logic, Polymer vision and so on since 2004, and lead the flexible display area. These kinds of interesting and technically progressive prototypes of flexible displays [6–8] make us have expectations for the flexible display products in the near future. However, it is seen that there are several hurdles to open the flexible display market. For example, most flexible displays are fabricated on the plastic or metal foil substrates, of which thermal stabilities hardly enable us to adopt the conventional process conditions. Instead, low temperature processes should be developed, but nevertheless the resultant thin-film transistors (TFTs) are required to have similar quality as conventional a-Si TFTs. In addition, it is desirable to be able to use the conventional equipments for dealing with the flexible substrates in the flexible display fabrication processes, which reveals some technical difficulties. Many efforts have been made to solve the above problems, including the research area of flexible substrates, low-temperature TFTs, and display modes. Recently, mass production for flexible EPD is expected to start from 2009 by LGD, Plastic Logic, and PVI, while flexible AMOLED's commercialization is expected in the near future by overcoming technological obstacles remained for mass production [9].

There are technological challenges remained for commercializing flexible displays in terms of substrate, active device, display mode, and process. Flexible substrate such as thin glass, metal foil, and plastic are required to have bendable, rugged, rollable properties. The active devices highly reliable at low temperature and materials insensitive to bending stress are required, so that a-Si TFT, Oxide TFT, and Organic TFT compatible to flexible substrate have been in the middle of being developed. In addition, display modes irrelevant to substrate bending have been developed using LCD, EPD, and OLED, while vacuum-less, printable, fast TAT and low temperature process are required to meet market needs such as low cost, fully flexible display.

To achieve bendable property, we can use a thin glass substrate that has thermal stability above 600°C, good chemical stability, low moisture permeability of less than 10^{-6}, and good transmittance of around 100%. But it is still brittle, fragile due to thin thickness of glass substrate. On the other hand, for the case of metal foil or plastic substrate, they are so rugged and durable that it can be bendable or flexible. A metal substrate has good thermal stability up to 1400°C, good chemical stability, and moisture permeability of less than 10^{-6}, but has opaque and rough surface, so that it should be coated barrier layer on the top of it to get smooth surface. However, a metal substrate has advantages such as thin thickness, ruggedness, and excellent barrier against oxygen and moisture [10]. Thus these metal substrates are promising candidates for flexible and eventually rollable display. Plastic substrate has many choices to use for a substrate such as PEN, PES, PI, PC, so that we can choose one of these plastic depending on the desired properties as shown in Table 1. That is, PEN has lower thermal expansion coefficient, resulting in less deformation or shrinkage issue during the process, while PI has a good heat resistance of 300°C but lower transmittance characteristics. PC has a good chemical resistance but relatively lower thermal stability, while PES may have shrinkage problem and lower chemical resistance. Plastic substrate has merits such as a lower moisture absorption, good chemical resistance, and better surface smoothness. Many reports about STN-LCD and MIMLCD using plastic substrates have been published [11,12]. However, overcoming issues such as low heat resistance and dimensional stability requires additional processing steps.

a-Si TFTs are a mature technology to use in low cost and large sized displays along with good uniformity. However, making the a-Si TFTs compatible with flexible substrates such as Stainless Steel metal foil and plastic substrate needs to reduce the process temperature from 320°C to 150°C or below, resulting in rather poor stability of a-Si:H

TABLE 1 Characteristic Comparison of Flexible Substrates: Plastic, Metal, and Thin Glass

	Plastic film				Metal	
Items	PEN	PES	PI	PC	STS	Glass
Heat Resistance	180°C	220°C	300°C	150°C	1400°C	>600°C
Chemical Resist.	Good	Stripper	Stripper	Good	Good	Good
Transmittance	90%	90%	85%	90%	0%	~100%
CTE (ppm/°C)*	13	40	20	30	10.5	4
Moisture permeability (g/m^2 day)	6.7	1 ~ 10	1 ~ 10	1 ~ 10	$<10^{-6}$	$<10^{-6}$
Density (g/cm^2)	~1.0	~1.0	~1.0	~1.0	7.75	2.37
Remark	Thermal stability	Shrinkage Chemical Resistance (NMP weak)	Yellowish (Transmittance] Chemical Resistance (NMP weak)	Thermal stability	Opaque Roughness	Brittle, fragile Thickness (0.1 t)

TABLE 2 Characteristic Comparison of Flexible Devices: a-Si TFT, Oxide TFT, and OTFT

Items	a-Si TFT	Oxide TFT	Organic TFT
Process	CVD	Sputter/CVD	Printing
Temperature	>100°C	<200°C	<150°C
TFT Mobility	$0.5\,cm^2/Vs$	$5 \sim 10\,cm^2/Vs$	$0.1 \sim 3\,cm^2/Vs$
TFT Reliability	Δ	○	Δ
Uniformity	○	○	Δ
Rollable Display	Δ	Δ	○
Tech. Level	Manuf.	Developing	Developing

TFT like threshold voltage shift (ΔV_{TH}) under bias temperature stress (BTS). On the other hand, Oxide TFT has a merit of good mobility of $5 \sim 10\,cm^2/Vs$, but still fabricated with CVD or sputter under the temperature of less than 200°C. Meanwhile, OTFT is suitable for using printing process, meaning that process temperature of less than 150°C is available, but it is still required to improve TFT reliability and uniformity in the panel. Table 2 summarized characteristics for each TFT device.

To implement flexible display, there are three representative modes available such as EPD, OLED, and LCD because of its availability for product technology. However, transmissive type display like LCD has a complex structure comparatively, and it is not easy to produce a good quality images when we bent it due to the distorted optical properties. Thus, reflective type or self emissive type mode such as EPD and OLED for display will be a main candidate for flexible display since they can reveal wide viewing angle and simple structure, and unlimited bending properties.

In a respect of process technology, low temperature TFT suitable for flexible substrate should be developed with a reliable device performance. If the Roll to Roll process is available, then all the processes for making TFT will be done at lower temperature without affecting the properties of flexible substrate, and it is also possible to fabricate flexible display with low cost. However, since printing process such as roll to roll has to be still improved or developed much more, current researchers have developed flexible display using hybrid technique that is mixture of conventional process and some part of printing process.

IV. FLEXIBLE DISPLAYS IN LGD

Relatively high process temperature, excellent dimensional stability, heat sink, and impermeability of metal foil except opaque allow us to be able to make transistors without any pre-processing such as pre-annealing and encapsulation using conventional TFT manufacturing technology. Thus, a metal foil substrate has been used for the initial flexible products based on self-emissive or reflective mode. On the other hand, a plastic substrate has lower thermal stability and permeability than metal foil, but its lighter, rollable, and transparent properties enable us to make flexible displays based on transparent mode. As the process technology for using plastic substrate has been improved continuously, future flexible display will be the form of conformable, foldable, and even disposable display.

The backplane we used comprises a-Si TFT fabricated using a conventional 5 mask process based on the bottom-gate back channel etch configuration as shown in Figure 3 [13]. Firstly, a multi-barrier structure was developed to reduce the surface roughness of the metal foil, and to protect chemical damage during the process before the a-Si TFT array fabrication. Then, the gate metals and source/drain metals were deposited by sputtering, and the a-Si, n^+a-Si, and SiN_x layers were deposited by plasma enhanced chemical vapor deposition (PECVD) at 150°C. The semiconductor and insulator layers are patterned by reactive ion etching, while the metal layers are patterned with wet etching. And, U-type dual TFT was applied to conventional design rules with W/L of 80/5, which has good initial characteristics and reliability equivalent to conventional device on glass with mobility of $\sim$0.6 cm^2/Vs and On/Off of $\sim 10^7$ as shown in Figures 4 and 5. In addition, BTS measurement for this low temperature a-Si TFT has

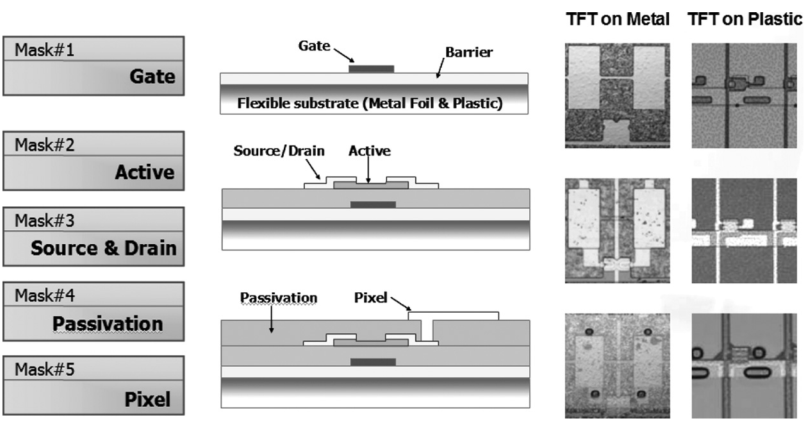


FIGURE 3 Flexible process flow and device structure on a metal substrate and a plastic.

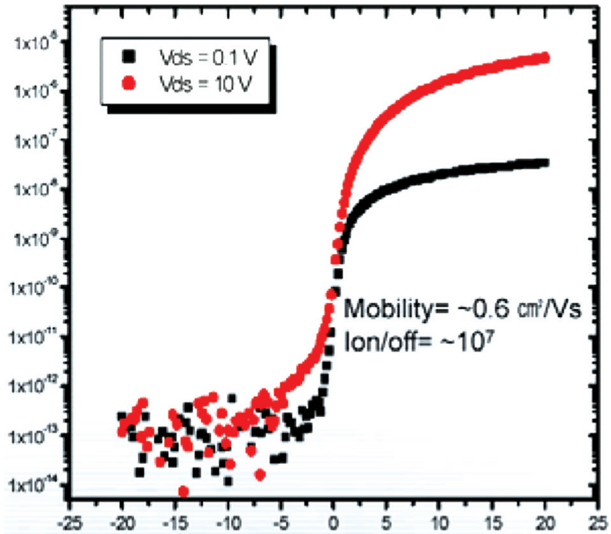


FIGURE 4 Initial transfer curve (left) $\mu \sim 0.6\,\mathrm{cm}^2/\mathrm{Vs}$, on/off of 10^7.

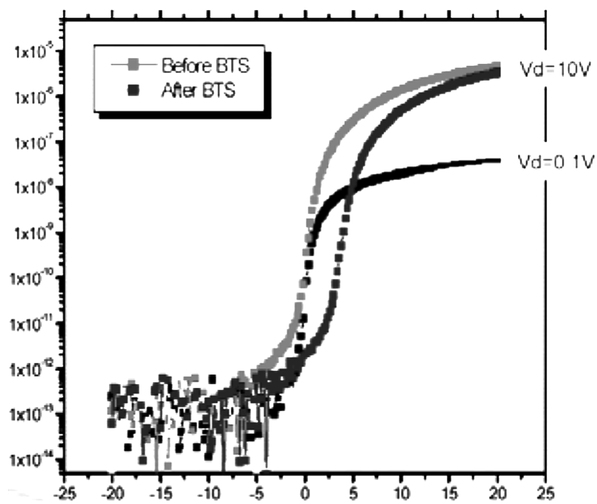


FIGURE 5 Transfer curves before and after BTS at 65°C for 1,000 seconds.

been done under a prolonged gate bias of 30 V and drain bias of 0 V ~ 10 V at 65°C for 1,000 seconds, and then shows ΔV_{th} of ~2.6 V.

We have developed world's first mono (W/B) and color flexible EPDs on a metal foil since 2005 by developing proprietary processing technologies that minimized the flexible substrate deformation and prevented the degradation of TFT/CF characteristics along with applying new kind of designs for the CF and the TFT. These flexible EPDs can provide high-information in e-book displays relevant to A4 size, which have the resolutions of 1280 × 800 pixels for mono and of 640 × 400 pixels for color with a unit dot size of 235 μm, and reproduce 16 shades of gray including 4096 colors for the case of color EPD. Additionally, we developed 14.3″ color flexible EPD with the world's highest resolution and vivid colors of virtual 256 gray levels for each R,G,B dots by applying color algorithm. Its high resolution and omni-directional viewing angle make it as easy to read as a printed page, and a reflective nature of the EPD eliminates the need for a backlight, making this display thin, lightweight and easy on the eyes. It also means that the display is extremely energy-efficient, only drawing power when the image changes. The display characteristics are summarized in Table 3. Moreover, we are going to mass-produce large size flexible W/B EPD on a metal foil within this year for the first time in the world.

Also, we have developed flexible AMOLED on a metal foil using similar low temperature process to EPD involving coating of thick planarization layer to reduce the surface roughness and the capacitive coupling between conductive substrate and TFTs. We employed a highly efficient top-emission OLED structure with phosphorescent emissive layer integrated with organic bank and multilayer thin film encapsulation to secure flexibility. 4″ flexible top-emission type AMOLED display based on a-Si TFT on a metal foil was developed for the first time and it has a curvature of bending radius less 5 cm along one axis, and a resolution of 100ppi (320×RGB×240) with vivid color reproduction as shown in the left part of Table 4. In order to manufacture reliable, flexible AMOLED displays with good picture quality, device process and OLED driving technologies need to be improved.

We also designed and fabricated low temperature TFT on plastic substrate to implement 12.1-inch flexible AMLCD. The fabrication process of TFTs on plastic substrate was almost the same as that on a metal substrate except the pre-annealing processing to reduce the misalignment in a later process. To solve the problems involving the plastic substrate's heat sensitivity such as dimensional stability, stress optimization, and misalignment between the two plastic substrates for TFT and CF, we developed new processing technique to

TABLE 3 Prototype Images and Features of Flexible EPD (14.1″ w/b & color, 14.3″ color, and 12″ w/b)

				
Items	14.1″ Flexible EPD (W/B)	14.1″ Flexible EPD (color)	14.3″ Flexible EPD (color)	12.0″ Flexible EPD (W/B): For MP
Resolution	1280 × 800 (WXGA)	640 × 400 (Relevant to VGA)	1280 × 800 (WXGA)	1600 × 1200 (UXGA)
Pixel Density	108 ppi	54 ppi	108 ppi	167 ppi
Active Area	301.4 (H)mm × 188.5 (V)mm		307.2 (H)mm × 192.0 (V)mm	266.8 (H)mm × 192.9 (V)mm
Number of Colors	Monochrome (16 Gray)	4096 color (16 Gray)	~16.7 M (quasi 256)	Monochrome (16 Gray)
Contrast Ratio	~10:1	~7:1	~8:1	~10:1
Viewing Angle	180* (All Directions)			
Illumination Mode	Refective			
Driving Voltage	±15 V			
Total Thickness	~300 μm			

TABLE 4 Prototype Image and Specifications of Flexible AMOLED (left) and AMLCD (right)

Items	Specification	Items	Specification
Panel Size	4″ diagonal	Panel Size	Diagonal 12.1″
Number of Pixel	320×RGB×240	Number of Pixel	800×(RGB)×600
Resolution	100 ppi	Resolution	83 ppi
Backplane	a-Si TFT on STS	Aperture Ratio	52%
OLED	Top-emission		
Number of Colors	16.7 M		
Brightness	100 cd/m^2 @F.W.		
Thickness	~250 um		
Gate-driver	Integrated		
Bending Radius	<5 cm		

fabricate the thin-film transistors, color filters and liquid crystals at process temperatures much lower than standard a-Si technology on glass substrate. The right part of Table 4 shows this flexible active matrix LCD, which reveals the features of full-color, high-resolution, lightweight, and bendable flexible LCD display with the resolution of 83ppi (800×RGB×600) and the aperture ratio of 52%.

In most cases of OTFTs, there are significant degradations in the device performance after conventional photoresist patterning because of damages on most organic semiconductors caused by the photoresist or the chemicals. Although a lot of efforts have been made to fabricate the OTFT-based display panel by using the shadow mask process, it is not feasible to obtain the high-resolution displays with this method. Recently, we have reported the new photolithography technique of the solution-processed organic semiconducting layer, resulting in the fine patterned OTFTs with excellent performances. Top-gated p-type OTFTs were fabricated using spin coating and photolithography. At first, Au/Cr source and drain electrodes were made by the thermal evaporation and wet etch process. After SAM treatment, the solution of the organic semiconductor and the organic insulator were coated on which the Au/Cr gate was deposited by the thermal evaporation. Active layers were patterned by our new photolithography technique and the dry etch process, on which the organic passivation material was coated by spin coating. After the contact hole opening process, the gate signal lines were patterned. Figure 6 shows the device structure. The performance of the OTFT at 140°C have been improved by annealing process, gate engineering and material development, resulting in increasing the mobility from $0.3\,cm^2/Vs$ to $1.1\,cm^2/Vs$ and on/off current ratio from over 10^5 to 10^7. These characteristics were one of the best results for the fine-patterned OTFTs made by the solution processes in the atmospheric environment. Then, the world's first 15″ XGA (86ppi) and SXGA (110ppi) AMLCD panels were fabricated with the solution-processed OTFT backplane. The channel dimension of the pixel transistor is $60\,\mu m/6\,\mu m$ for both cases as shown in Table 5.

With ever increasing demand for a larger glass size in the TFT-LCD and flexible display, there is a need for new technologies for patterning which can overcome the limitations of photolithography such as a tremendous investment cost. Some of those are the development of the mask reduction process for simplifying process steps [14], Ink-jet technology for color filter fabrication and related things to reduce the material cost dramatically [15], and so on. Since one of the processes that increase the cost most highly in the TFT manufacturing is a photolithography, we have developed the roll printing technology to generate TFT pattern without photolithography process (Fig. 7). The roll printing method has been modified slightly from the traditional gravure offset printing process as follows. After coating the

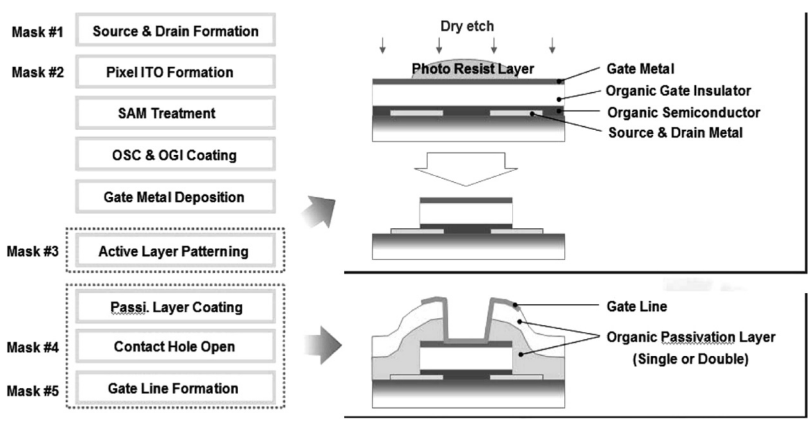
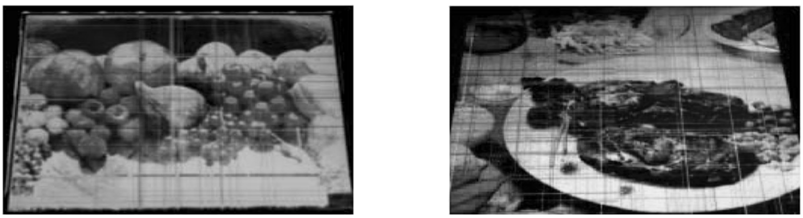


FIGURE 6 Organic TFT process flow and its device structure.

TABLE 5 Prototype Image and Specifications of AMLCD Panel Fabricated by The Solution Processes: World' Fist 15″ Panel (left) & World's Highest Resolution 15″ SXGA Panel (right)



Item	Specification	Item	Specification
Panel Size	Diagonal 15″	Panel Size	Diagonal 15″
No. of Pixel	1024 × RGB × 768 (XGA)	No. of Pixel	1280 × RGB × 1024 (SXGAG)
Resolution	86 ppi	Resolution	86 ppi
TFT W/L	60 μm/6 μm	TFT W/L	60 μm/6 μm

ink on the soft blanket by which a large roll was rounded, we rolled it onto the cliché that has patterns. This rolling process played a role of removing unnecessary patterns before transferring. Then, we transferred the necessary pattern remained on the blanket roll onto a glass.

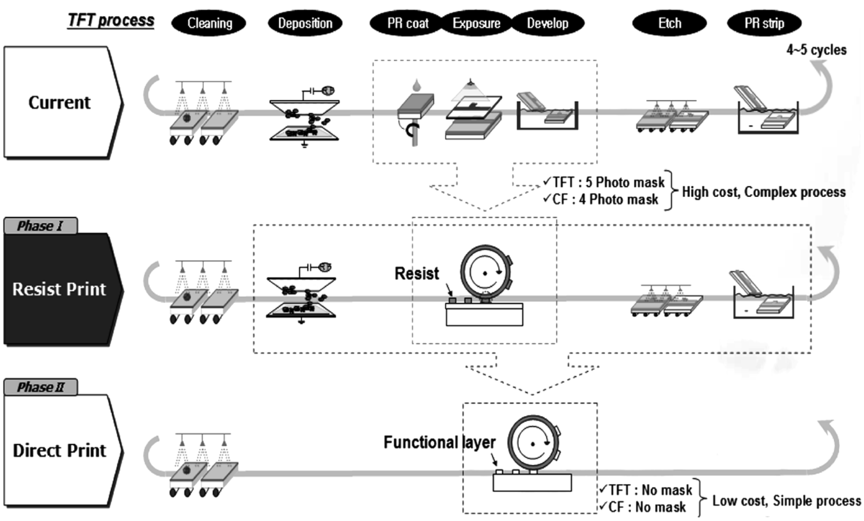


FIGURE 7 Roll printing process flow with showing technology direction of it.

However, it is difficult in this traditional Gravure offset printing that the surface energy of ink is in between that of the blanket and the glass in order to shift the ink from cliché to blanket and then from blanket to glass. On the other hand, in our method, a pattern generation is possible if the ink is transferred just from the blanket to the glass and the cliché regardless of transferring order. In addition, this new method can make the thickness of the resist ink thin and uniform for fine pattern generation. From this point of view, this process presents a great advantage to make a fine pattern. Using those concepts, we have decided to make 15″ XGA LCD panel adopting TN mode because TN mode is good for straight and block designs to make a deviation of accuracy and pattern shape minimized as well as to evaluated this photo-less process. We have started to study traditional printing process and could find a way to apply it as a process of TFT-LCD fabricating; the characteristics of pattern properties, position accuracy, printing materials, and design concept for making the panel, so we could develop the World's 1st TFT-LCD panel by all layer printing processes based on the roll printing method. This prototype in Table 6 has a resolution of 85ppi (1024×RGB×768), sub pixel size of 297 μm × 99 μm, and the minimum feature size of 6 um, which shows the possibility that the roll printing process will be able to take place of the conventional process.

Among various flexible display devices, EPDs are currently considered as the most available flexible display technology because of their simple process and very low power consumption along with thin, lightweight and easy on the eyes properties. Active matrix OLED

TABLE 6 Prototype Image and Features of AMLCD Fabricated by All Layer Printing

Item	Spec. & Features
Display size	15″ TN
Resolution	1024 × RGB × 768 [XGA]
Sub-pixel	297 × 99 μm (85 ppi)
Process	5 resist printing steps for TFT (Gate, Act, SD, Via hole, Pixel) 4 printing steps for CF (1 layer resist printing for BM 3 layer CF printing, R,G,B)
Specification	Min. feature size: 6 μm Line/space of channel: 6/7 μm Hole size : 10 × 20 μm

(AMOLED), on the other hand, is an emissive type display device, supposedly has a better picture quality, such as brightness, color, contrast ratio, viewing angle and response time compared to AM-LDCs. An OLED is a thin film solid state device, which makes it easier to apply to flexible display because of its relatively simple fabrication process and less optical distortion according to the geometric form of display. Thus, LGD is currently focusing on developing AMEPD and AMOLED in this regard. Flexible EPD is expected to be used for Niche market at first stage, then will have many applications like large digital signage that needs conformal and memory effect, while flexible AMOLED will be used for the premium flexible display with a high quality moving image, and thereafter, will create new consumer electronics application area in the future. In order to achieve the above flexible display, LGD has a technology strategy for substrate, process, and device, respectively. For the substrate, we are now mainly using a metal foil as a substrate to achieve bendable, rugged, durable properties, but finally will use plastic substrate to implement rollable or conformable display. In case of process, we are now making flexible display based on the conventional vacuum plus photo process while evaluating vacuum printing process, but all the processes for making the flexible panel will be printing process in the end. Moreover, a-Si TFT device is now adopted to fabricate an active matrix backplane on a flexible substrate to use current LCD infrastructure, but soluble TFT suitable for flexible display like OTFT will be used for forming switching array on a plastic substrate in the near future.

V. SUMMARY

The future display market demands ubiquitous display devices that are more portable, fashionable and environment friendly. Display manufacturers need to advance their technologies to build a lighter, slimmer, rugged and low power consuming devices, as well as to improve the picture quality. Active matrix flexible display is an emerging technology widely being developed in order to fulfill the needs of the next generation displays. However, technological challenges in terms of Substrate, Device, Mode, and Process are remained to commercialize flexible displays. LGD has demonstrated the flexible mono & color EPD with largest size, a-Si based AMOLED on a metal foil, large size flexible AMLCD on a plastic substrate, and AMLCD panel with the OTFT backplane using the solution-soluble organic materials for the first time in the world. Our remarkable developments of the low-temperature a-Si TFTs, organic TFT, and roll printing technology allow us to realize rollable, low price, and even disposable displays and reveal the strong possibility of flexible display for coming into the new biz market in the near future. Moreover, it is plausible to guess that the combination of the organic electronics and the printing techniques can offer a new approach to large area flexible and low-cost integrated devices.

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