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Technology Advances in Flexible Displays and Substrates

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ABSTRACT This paper reports the latest technological advances made by the Industrial Technology Research Institute (ITRI) in flexible displays, especially the flexible substrate, thin-film transistor (TFT) backplane, and active matrix organic light-emitting diode display. Using the leading cholesteric liquid crystal technology of ITRI, we develop a rewritable, environmentally friendly thermal printable e-paper. The e-paper, devised to reduce traditional paper consumption, achieves a high resolution of 300 dpi with a memory function. In addition, we report on the ITRI's initial success in demonstrating a complete R2R process for multisensing touch panels on 100-μm thick flexible glass substrates provided by Corning.

INDEX TERMS Active matrix organic light-emitting diode display (AMOLED), cholesteric liquid crystal (ChLC), flexible substrate, roll-to-roll process, ultrathin flexible glass.

I. INTRODUCTION

Because of the mega trend of the market demand for personal mobile devices, the Industrial Technology Research Institute (ITRI) has recently dedicated a significant portion of its R&D resources to the development of next-generation electronic displays, which are thinner, lighter, and easier to carry and store. These new displays can be bent and, in some cases, even folded, or rolled, which was unthinkable with previous displays. This is largely because the rigid glass part of a traditional flat panel display can now be replaced with plastic or ultrathin glass. ITRI has developed cross-divisional, multidisciplinary teams that engage engineers and scientists with broad professional backgrounds and training. This paper reports ITRI's latest technological advances in flexible displays, particularly flexible substrates, thin-film transistor (TFT) backplanes, and active matrix organic light-emitting diode displays (AMOLED). Numerous people in the display industry are increasingly considering roll-to-roll (R2R) manufacturing for its potential in reducing the cost of slower batch processing and capital-intensive vacuum-based processing. At ITRI, flexible displays are manufactured using a sheet-to-sheet vacuum process (i.e., FlexUP technology) or an R2R method (display and touch panel module). This paper presents recent progress in three projects: flexible universal planes (FlexUP), rewritable electronic paper, and a full R2R process with 100-μm-thick flexible glass substrates.

II. GLOBAL TRENDS IN MARKET AND TECHNOLOGY DEVELOPMENT

Of the many critical components in personal mobile devices, the display is perhaps the most important because it facilitates interactions between man and machine. Recent trends in the development of screen technology have focused on the form factor, energy conservation, and eco-friendliness. Flexible displays have enormous possibilities to provide solutions that are light, thin, and foldable. Meanwhile, e-paper-based bistable displays have the potential to meet the need for displays that conserve energy and can operate for long periods without recharging. At the same time, R2R technology is poised to be an important core technology in the future market for environmentally friendly, reasonably priced printed electronics.

Researchers have made enormous achievements in the development of display technology over the past decade. Advanced thin-film transistor liquid crystal display (TFT-LCD) technology applications have become commonplace, and South Korea's Samsung Display Co. Ltd. is already producing active matrix organic light-emitting diode displays (AMOLEDs) using glass substrates at its 4.5- and 5.5-generation plants. These products are already being seen in applications in smart handheld devices such as smart phones and tablets, and AMOLED production technology using plastic substrates is under development among display manufacturers. Samsung Electronics Co. and LG Electronics have already announced that they will introduce flexible AMOLED products to the marketplace in the second half of 2013. In addition to Samsung Display Co. and LG Display Co., the Industrial Technology Research Institute (ITRI) is one of a handful of research institutions in the world that has developed flexible AMOLED core technology.

According to recent research by the ITRI on the market value of flexible AMOLED display applications, the appeal of this technology in the most preliminary stage is that the displays are light in weight and unbreakable. Personal mobile devices serve as the driving force of these displays, and increasing demands are being made to meet the battery capacity and lightweight needs of these devices. The proposition in the second stage is for the individualization and development of a framework for foldable products. The driving force behind this development includes trendy designs and personal wearable applications, such as health-monitoring devices, local-based services, handsets, foldable tablets, and smart phones (Fig. 1). According to ITRI estimates, the output value of flexible AMOLED panels in 2020 will reach US$37 billion. In addition, flexible AMOLED technology and products, after progressing through the ‘‘unbreakable, curved, wearable, and foldable’’ development stage (Fig. 2), will undoubtedly pave the way to a design revolution in display products [1].

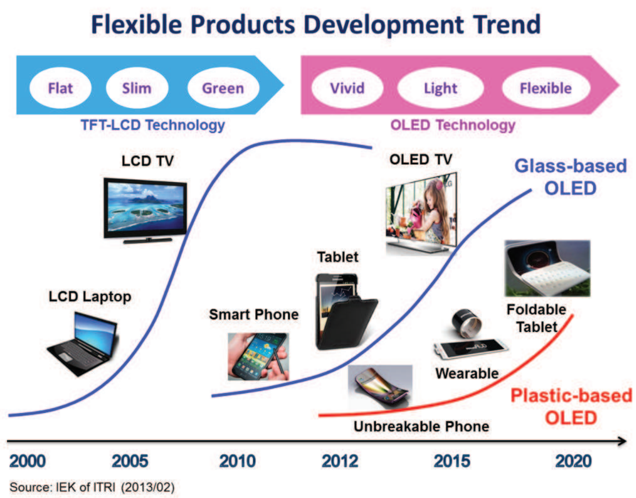


FIGURE 1. **The gradual emergence of plastic substrate-based AMOLED display applications.**

Many industry analysts have recently become extremely bullish on the prospects of next-generation energy-saving display technology involving e-paper and bistable displays, including electrophoretic, electrowetting, and Cholesteric LCD (ChLC) technologies. Taiwan’s E Ink Holdings Inc. and Japan’s Bridgestone are leaders in electrophoretic technology, whereas Liquavista of the Netherlands, University of Cincinnati, and Taiwan’s ITRI are pioneering electrowetting technology. Finally, Kent Display Inc., ITRI, and Japan’s Fujitsu are among the leaders in ChLC technology. In addition, ITRI research shows that printed electronics based on

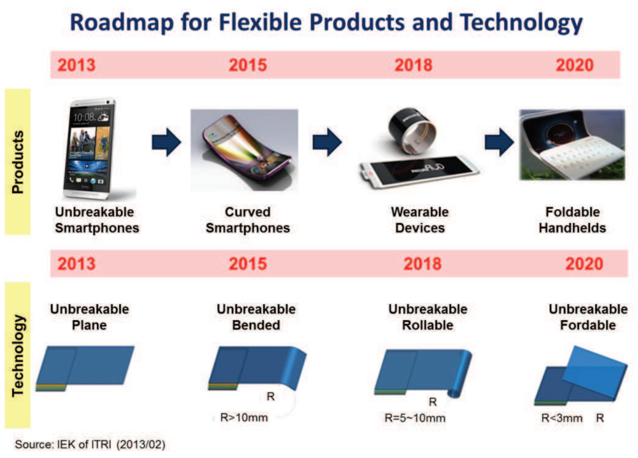


FIGURE 2. **Progression in the development of flexible AMOLED technology and products.**

R2R technology will have wide-ranging RFID applications in the future, including sensors, batteries, solar cells, lighting, and fuel cells. The global output of flexible electronics in 2022 will likely reach US$65 billion, indicating virtually unlimited business opportunities on the horizon. Already, ITRI has gained significant R&D achievements in flexible AMOLEDs, ChLCs, and thin-glass R2R technology.

III. ITRI’S TECHNOLOGICAL ADVANCES

A. FLEXIBLE UNIVERSAL PLANE

To fulfill the requirements of advanced displays, such as thinness and a light and robust design, researchers have long aspired to develop a flexible AMOLED. Because a flexible AMOLED can be bent, folded, or rolled, it is foreseeable that smart phones and tablet PCs can be converged in future designs (Fig. 3).

FIGURE 3. **Developmental trend of handheld devices.**

To render the active matrix displays flexible, the Flexible Universal Plane (FlexUP) technology of ITRI inserts a thin layer of release material between a polyimide (PI) layer and a glass carrier to be processed in the existing TFT processing line. The TFT array used for the flexible display is composed on a high-temperature stable PI film that is subsequently removed from the glass carrier without damaging the transistors on the PI film. In principle, the FlexUP technology can be applied to LCDs, as well as OLEDs. Nevertheless, AMLCDs have two major issues: 1) the cell gap is difficult to control when the panel is bent, which could result in poorer image quality; and 2) a flexible backlight is required for AMLCDs, making the structure far more complex. One of the first demonstrations of FlexUp technology was a 6-in. color flexible AMOLED display featuring a bending radius of less than 1 cm. When folded at a bending radius of 1 cm or less, the 0.01 cm ultrathin screen is still able to continue displaying images with a brightness of up to 150 nits. Furthermore, the screen can be flexed up to 100 000 times without affecting the display function. Although flexible AMOLEDs possess many desirable properties, several development issues persist such as: high-temperature stability of the flexible substrates, high-performance low-temperature TFT processes, highly flexible and reliable OLEDs, and touch panels (Fig. 4). To overcome these challenges, ITRI has been developing several unique technologies to realize flexible AMOLEDs since 2006.

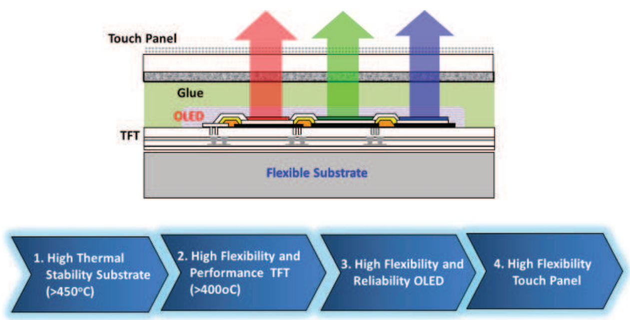


FIGURE 4. **Challenges of flexible AMOLEDs.**

Most flexible substrates are currently prepared by laminating or coating them on glass carriers, followed by fabricating TFT devices on the substrates. The structure of the laminated substrate consists of metal or plastic foil (e.g., PC, PET, PEN, PES, and PI) on top of a rigid glass carrier, with adhesive glue in between. However, lamination technology has three inherent issues: poor layer-to-layer alignment, residual glue after debonding, and TFT processing-temperature limitations. Therefore, ITRI has developed the FlexUP technology by coating a PI solution directly onto the glass substrate with a debonding layer (DBL) (Fig. 5), followed by fabricating TFT devices on the PI substrate, and the final residue-free debonding of the substrate from the glass carrier [2]. FlexUP technology is compatible with existing TFT manufacturing facilities, and the alignment accuracy of the TFT process can be maintained at approximately 1 μm on a Gen 2.5 size substrate (370 mm × 470 mm). FlexUP technology, theoretically, can also be applied to various applications, including flexible OLED lighting, flexible photovoltaic cells, flexible sensor arrays, and digital X-ray sensor arrays.

The coating-type substrate includes polymeric solutions (e.g. PI) [3]–[5], debonding layers, and a carrier glass.

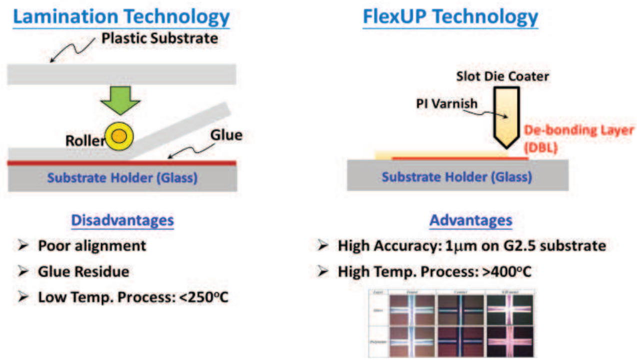


FIGURE 5. **Flexible substrate-handling technology comparison of lamination and FlexUP.**

In 2011, ITRI developed a novel colorless PI for amorphous-Si TFTs and touch panel applications. The thermal stability and coefficient of the thermal expansion (CTE) of PI are 350 °C and 60 ppm/°C, respectively. For higher processing temperature, ITRI recently developed a yellowish PI for LTPS TFT integration. The thermal stability and CTE have since been improved to 450 °C and 7 ppm/°C, respectively (Table I).

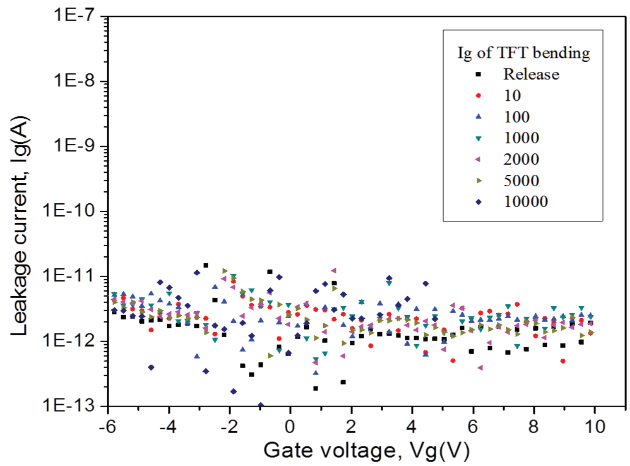


FIGURE 6. **Effect of substrate bending on TFT performance.**

The development of flexible high-performance TFT backplane technologies on FlexUP is on-going. Because low-temperature poly-Si TFTs (LTPS TFTs) and IGZO TFTs (indium gallium zinc oxide TFTs) are excellent semiconductors for OLED driving, they are highly desired for AMOLED technology. The BCE-type (backchannel etching) amorphous-IGZO TFTs were fabricated on a FlexUP substrate by using a four-mask process with a process temperature less than 300 °C. Fig. 6 shows the bending performance of a BCE-type amorphous-IGZO TFT. The amorphous-IGZO TFT backplane was bent at a 25 mm radius up to 10000 times, with the leakage current maintained below 10−11 A. An obvious Vth shift of 0.5 V occurred when the TFTs were first released from the carrier, whereas a shift of less than 0.1 V was observed after a 10000-time bending test. A 2.5% degradation in TFT output current occurred when the device

TABLE 1. ITRI'S Polyimide Substrate Development.

	2008	2011	2012
Materials	Colorless Polyimide	Colorless PI	Yellowish PI
Thermal Stability (°C)	230	350	450
CTE (ppm/°C)	60	40	7
Applications	Amorphous-Si TFT, Touch Panel	Metal Oxide TFT, BE OLED	LTPS TFT, TE OLED

was released, and a degradation of less than 1% was observed after the extensive bending test. These results show that the amorphous-IGZO TFTs have excellent bending resistance properties when the bending radius is 25 mm. The release process is a critical step because the mechanical and residual stress incurred during this process can affect the TFT device directly.

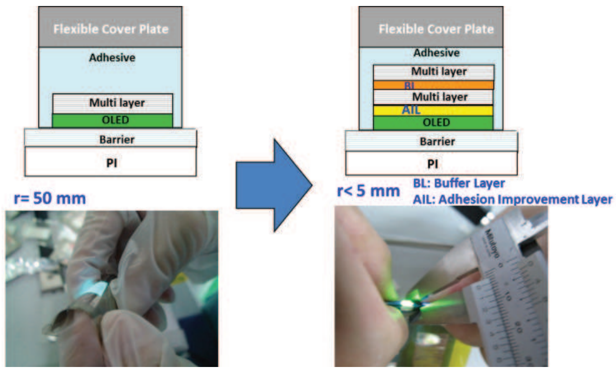


FIGURE 7. The flexibility improvement of new OLED device structure.

A flexible OLED has the same emitting device structure as a glass-based OLED. However, without the glass protection, the passivation and encapsulation for a flexible AMOLED is far more challenging. The ITRI passivation structure includes an inorganic water-resistant layer and a buffer layer (BL), as shown in Fig. 7. The inorganic layer serves as a primary barrier against moisture and oxygen infiltration from the environment. Meanwhile, a soft BL works to offset the stress generated by the bending process. This soft buffer layer, together with an adhesion improvement layer (AIL), between the passivation layer and the OLED layer (OLED/AIL/Inorganic Multilayer/BL/Inorganic Multilayer), effectively improves the flexibility of OLED further from bending at a radius of 50 mm to less than 5 mm without cracks (Fig. 7).

ITRI has integrated several technologies—the FlexUP, highly flexible TFT processes, highly flexible and reliable OLEDs, and touch panels—into a novel and flexible touch-sensitive AMOLED display. A flexible AMOLED display was demonstrated by implementing a 2T1C circuit backplane, and subsequent deposition of a color OLED structure on the TFT backplane. Fig. 8 shows the progression from a 4-in. monochrome AMOLED to a 6-in. flexible color AMOLED that can still function normally in water. The total thickness of the 6-in. flexible AMOLED display is approximately 65 μm, which can be bent to a curvature radius of 5 cm for 100 000 times and still retaining its functionality. In 2010, ITRI

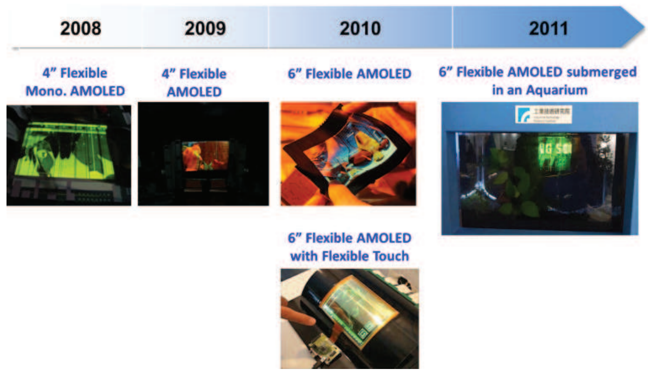


FIGURE 8. Flexible AMOLED display development at ITRI.

successfully integrated an ultrathin touch panel with the flexible color AMOLED. This was the first flexible touch AMOLED ever demonstrated in public. The flexible AMOLED was tested in an aquarium for 1 week to demonstrate that our technology could withstand a high-moisture environment.

B. REWRITABLE ELECTRONIC PAPER–i2R e-PAPER

Green technology has been discussed and developed for numerous environmental considerations. E-paper technology is the most attractive alternative for replacing paper and eliminating the energy associated with producing paper as well as saving trees. Working with Eastman Kodak Company, ITRI has developed an i2R e-Paper based on the technology of ChLCD by using a cost-effective R2R process and a simple single-substrate structure, the result of which is e-paper 3 m in length. The i2R e-Paper is rewritable and reusable with high-resolution capability (300 dpi). It has a contrast ratio of more than 10:1, multiple colors (i.e., red, blue, green, and purple), and high reliability (with rewritability of more than 500 times). Novel applications have been introduced for e-banners, e-cards, e-signage, e-badges, and e-tickets, with several electrical addressing and refreshing mechanisms.

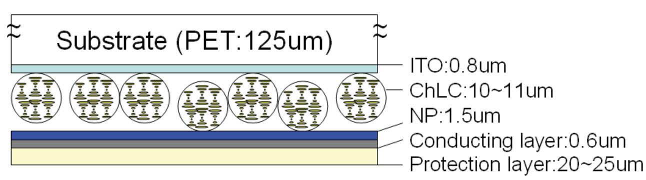


FIGURE 9. Schematic cross-section diagram of an i2R panel.

The i2R e-Paper boasts a single-substrate design with five functional layers comprising the ITO layer, ChLC layer, nano-pigment (NP) layer, conducting layer, and protection layer (Fig. 9) [6], [7]. Voltage is applied between the ITO and conducting layers to switch the ChLC into the different states. The ChLC layer is composed of an encapsulated ChLC and gelatin to reflect a certain wavelength of incident light. The NP layer also reflects a certain wavelength of incident light. To prevent user damage to the liquid crystal, a protection layer composed of polymer and silica particles is coated on top of the NP layer.

The ChLCD was selected for e-paper technology because of its bistability characteristics, no backlight requirement, and multi-color possibilities without a color filter. The bistability feature represents two stable states (i.e., the planar and the focal conic states) based on the direction of the molecules in the ChLC. These two stable states can maintain the status without power consumption, and voltage is required only when the ChLC is changed from one state to another. Because the ChLCD shows images by reflecting ambient light, a backlight is unnecessary. Different colors are displayed using different ChLC designs without a color filter. For example, if the ChLC is designed to reflect yellow light and the NP layer reflects blue light, the planar state emits a white image from the reflected yellow and blue light [Fig. 10(a)]. The focal conic state indicates that the incident light is scattered by the ChLC and only the blue light is reflected by the NP layer [Fig. 10(b)].

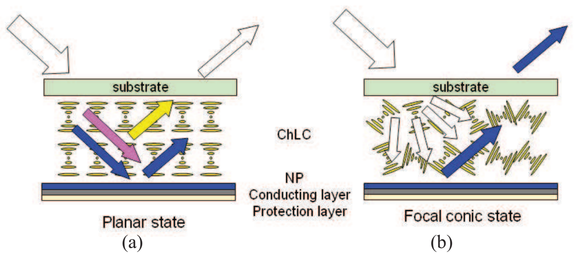


FIGURE 10. **Two stable states of i2R e-paper: (a) planar state, and (b) focal conic state.**

ITRI, collaborating with Eastman Kodak Company, has implemented an R2R process for fabricating i2R e-Paper with a process flow consisting of laser patterning, slot-die coating, sputtering, screen printing, and cutting (Fig. 11). A 125-μm-thick PET film with an ITO layer is used for the substrate of the i2R e-Paper. The laser patterning of the ITO layer has the advantage of being a simple and dry process for maintaining the dimensional stability of the substrate compared to that of the wet-etching process. The slot-die process coats two layers of the ChLC and NP simultaneously, with high throughput and good uniformity. The ChLC layer consists of a mixture of encapsulated ChLC and gelatin at a ratio of 11:2, and is cured at approximately 40 °C to cross-link the gelatin, making it highly durable to physical pressure. The conducting layer consists of sputtering aluminum (Al) with a thickness of approximately 0.6 μm, which serves a dual role of electrical and thermal conduction. After the screen printing of the protection layer, the i2R e-Paper is cut into the final dimensions. ITRI demonstrated a 3-m-long e-paper with the R2R process, which theoretically has almost no length limitations (Fig. 11) [8], [9].

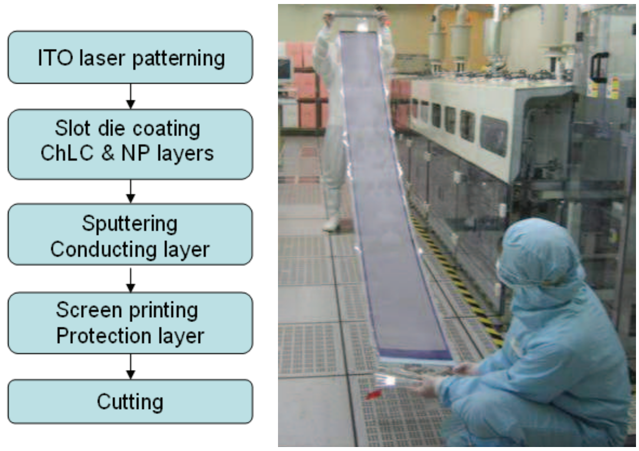


FIGURE 11. **The R2R process flow of i2R (left) and finished e-paper measuring 3 meter long (right).**

This i2R e-Paper is suitable for various applications, including bulletins, banners, and signage. The e-paper can be addressed electrically by applying a voltage of approximately 100 V to change the ChLC from the focal conic state to the planar state. The segmented driving method can pattern the conducting layer into pre-designed figures, and shows a fixed picture turning on and off to attract customer attention [Fig. 12(a)]. The i2R e-Paper is also suitable for e-signage based on a passive matrix-driving method with a resolution of 75 dpi, which exhibits detailed promotional information for on-sale products [Fig. 12(b)].

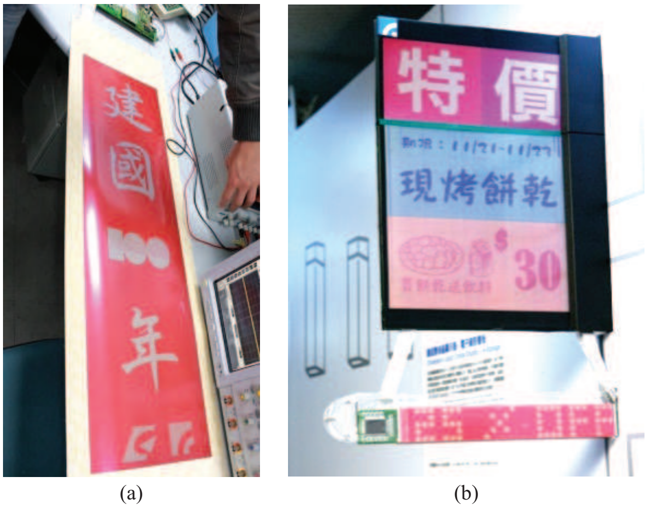
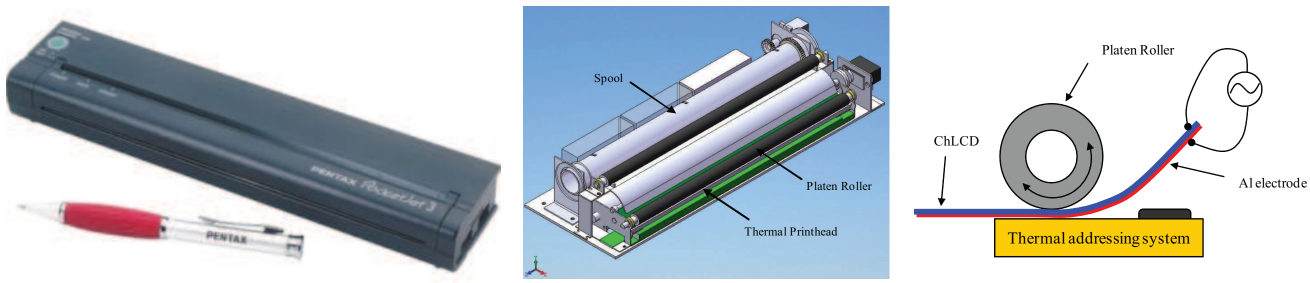


FIGURE 12. **The passive matrix addressing (a) an e-banner and (b) an e-signage.**

ITRI also developed another novel thermal addressing mechanism by using a commercial portable thermal printer (Pentax PocketJet 3), as shown in Fig. 13(a). With a roller inside the thermal printer module, the e-paper is rolled through the thermal printhead, and the heat that is generated



(a) (b) (c)

FIGURE 13. **(a)The commercial portable-thermal printer Pentax PocketJet 3, (b) the mechanical structure of thermal-printer module, and (c) addressing mechanism.**

FIGURE 14. **Demonstration of a Chinese landscape painting with the thermal addressing i2R e-paper.**

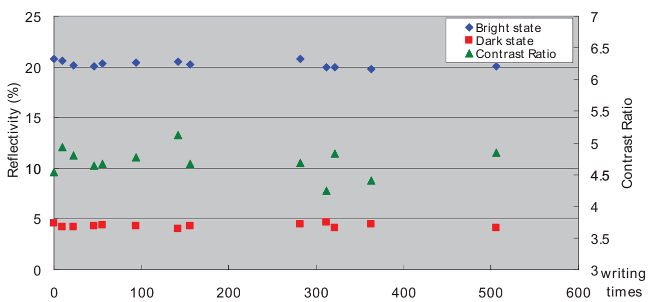


FIGURE 15. **The reliability results of the re-writing test.**

can reverse the state of the ChLC [Fig. 13(b)]. The simultaneous application of bias voltage to the ChLC layer during the thermal printing process could improve the contrast ratio to more than 10:1 [Fig. 13(c)] [10], [11]. We demonstrated a 3-m-long e-paper by using the thermal addressing mechanism with a 24-cm-wide 300 dpi thermal print head showing an ancient Chinese landscape painting (Fig. 14). The reliability was verified by writing and rewriting on the i2R e-Paper more than 500 times, thereby demonstrating the stability of a reflectivity greater than 95%, and a contrast ratio better than 4.5:1 (Fig. 15).

At ITRI, novel applications of e-Paper have been proposed with various prototypes such as e-cards with fine pictures, e-tags showing detailed information, e-badges with visitor data, and e-tickets similar to printed paper tickets (Fig. 16). Additional e-Paper applications could still be possible from creative business model innovations and further technological improvements. For example, if an e-ticket with a QR code [Fig. 16(d)] were to be used in Taiwan's high-speed trains, paper ticket usage could be reduced by more than 40 million pieces per year.

This e-ticket could also be used for transportation vehicles, movie theaters, museums, and theme parks. For other future applications, it would be desirable to further improve the performance of i2R e-Paper, such as a higher resolution (line width smaller than 85 μm), more rewriting times (more than 600 times), and multiple colors (e.g. multiple area-colors in one panel.)

C. ROLL-TO-ROLL PROCESS TECHNOLOGY AND TOUCH PANEL MODULES WITH ULTRA-THIN FLEXIBLE GLASS

ITRI has recently developed advanced technology with a R2R processing on the ultra-thin glass. Numerous researchers believe that R2R process technology will replace the existing stand-alone chamber process, which is an energy-consuming process that requires high-voltages, high vacuums, and high temperatures. The stand-alone chamber process is also a time-consuming process because it processes one substrate at a time. Conversely, the continuous rolling process is faster. The R2R process can be configured to require low voltage, atmospheric pressure, and room temperature. Therefore, the R2R process can be a lightweight production method.

From October 31 to November 2 of 2012, ITRI demonstrated its cutting-edge R2R process on Corning Willow Glass, a 100 μm ultra-thin flexible glass substrates, in Yokohama, Japan, at the industry trade show Flat-Panel-Display International. Drawing inspiration from the R2R process used to create newspapers, the manufacturing technology of ITRI overcomes previous difficulties in the R2R manufacturing facility and process integration. ITRI is the first to successfully fabricate touch-panel modules with a complete R2R process on 100 μm ultra-thin flexible glass substrates. In addition to touch-panel devices, this R2R technology can be extended to other applications, such as smart phones, tablet PCs, notebooks, flat panel displays, solar panels, and organic light-emitting diode lighting.

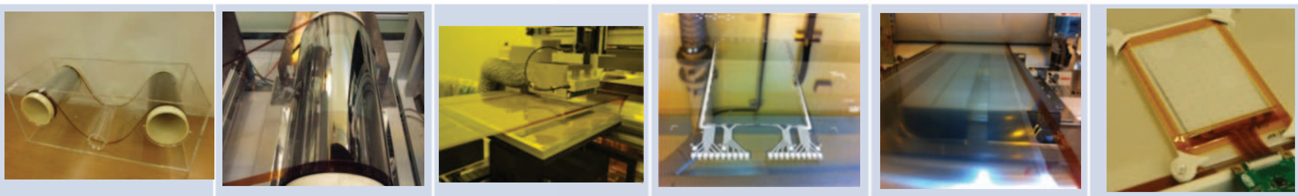
(a) (b) (c) (d)

FIGURE 16. New applications of e-paper for (a) e-card (6 cm × 9 cm), (b) e-tag (13 cm × 16 cm), (c) e-badge (6 cm × 9 cm) and (d) e-ticket (5.4 cm × 8.5 cm).

FIGURE 17. Photo of the R2R machine with dual functionality: (1) Incoming quality control in the far end, (2) Lamination in the near end of the photo.

Using Corning's Willow Glass offers several advantages for end-users of the final products. Because the touch panel has a thickness of only 100 μm, it enables thinner and lighter designs that can be bent to a curve. It also eliminates the need to grind the glass from 400 to 200 μm in the conventional process without sacrificing the device performance and reliability. Finally, this revolutionary process of continuous processing on ultrathin glass reduces production costs.

In developing the complete R2R process, ITRI has designed and built four machines feeding 100-μm glass spools. The first R2R machine is a quality-control tester to screen the incoming glass spools. This machine also laminates the ultra-thin glass to another spool of thin substrate, such as PMMA or other types of optical films. The second R2R machine is a laser ablation tool that patterns the ITO films on the glass to create the sensor arrays of the touch panels. The third R2R machine is a screen printer that can print dielectric layers, insulation layers, and metal runners. The fourth R2R machine is a slot-die coater that coats thin organic layers for various purposes. Fig. 17 shows a photo taken of the first machine. The two white rollers in the middle of the photo are used for the lamination function [12], [13].



General	Winding/ Rewinding	Laser Patterning	Screening Printing	Lamination	TP Module
◆ Glass thickness: 100 μm ◆ Laser patterning line width: 15 μm ◆ Screen printing line width: 100 μm ◆ Lamination quality: bubble free, glass crack free	◆Winding shift < 500 ppm without auto correction ◆pass 6" and 9" rollers with a 180° wrap angle ◆ Winding speed: 3 m/min	◆Tension: 2 kgf ◆Laser wavelength: 1064 nm ◆Line width: 30 μm ◆Laser pattern accuracy: 15 μm	◆Screen Printing line width: 100 μm ◆Alignment accuracy ≤ 10 μm ◆Printing accuracy ≤ 50 μm	◆Lamination accuracy < 200 ppm without auto correction ◆Lamination quality: bubble free, glass crack free ◆Winding speed: 1 m/min	◆TP quality: fully functional 3.5" panels ◆Metal Bridge Line resistance < 2 kΩ ◆ITO line resistance < 4 kΩ

FIGURE 18. Key results of R2R technology including individual process stations and fully integrated touch panels.

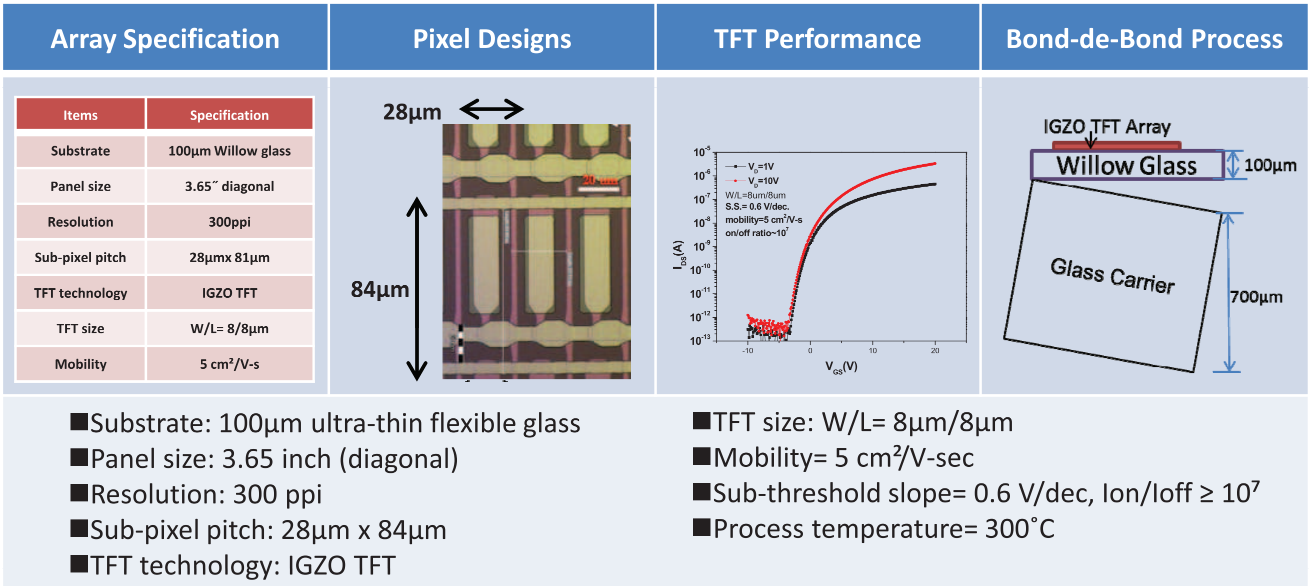


FIGURE 19. Results of the IGZO TFT array fabricated on 100-μm ultrathin glass with a bond/de-bond process.

Fig. 18 presents a summary of the major R2R breakthroughs achieved at ITRI [12], [13]. This figure includes both the individual process stations and the fully integrated devices of the touch-panel modules. One of the critical challenges in R2R technology is the overlay resolution among different layers of the integrated structures. For glass substrates, this is affected primarily by two factors: the R2R winding shift of the conveyance system and the layer-to-layer alignment accuracy. As the figure shows, the winding shift without auto-correction is less than 500 ppm, and can be further improved with auto-correction. The layer-to-layer alignment accuracy is closely related to the distortion properties of the substrates. The distortion comes from mechanical stress and thermal expansion during the process. This system achieves an alignment accuracy of better than 10 μm.

As an interface device for smart phones and tablet PCs, touch panels must manage multiple inputs simultaneously. In addition, for consumer electronics, achieving an input resolution that is sufficiently smooth for finger strokes in writing is crucial. The 3.5″ touch panel in Fig. 18 is capable of five-finger inputs. This level of performance requires a high signal fidelity, which conventional processes achieve through high-temperature and high-vacuum processes to minimize the line resistance and overlap capacitance. In contrast, the process conditions of the R2R system of ITRI require only room temperature and an atmospheric environment to achieve a similar performance with excellent signal fidelity. Consequently, we are able to use a commercially available driver IC for the touch panels. The driver IC sets the compliance limits of the line resistance and overlap capacitance. For the input resolution of the finger strokes in writing, most driver IC designs use differential pairs and interpolation algorithms among the adjacent signal lines. Thus, the uniformity of the line resistance and overlap capacitance is crucial. On the 3.5″ touch panels fabricated with the R2R process, we can write sentences with English words and Chinese characters the size of a fingertip. This performance indicates a uniform line resistance and overlap capacitance.

The display resolution of smart phones, tablet PCs, and notebook PCs has improved continuously in the past few years, and currently is above 300 ppi. For large displays in TVs and monitors, the display resolution has increased to 3840 × 2016 for TVs and 1326 × 768 for typical monitors. Several higher-end monitors have increased the FHD resolution of 1920 × 1080 [14]. Following this trend, display technology has also shifted from conventional amorphous-Si TFT arrays to IGZO oxide TFT arrays, which can produce a higher electron mobility for high-resolution displays.

ITRI has successfully demonstrated its IGZO oxide TFT technology on 100-μm thick flexible glass substrates by applying an innovative bonding/debonding (BDB) process.

Similar to the FlexUP technology, this BDB process bonds the 100-μm ultrathin glass to a conventional glass substrate. The TFT array is then fabricated with the existing production lines. The ultrathin glass substrate can be debonded afterward. Because of the excellent characteristics of flexible glass, the device can be fabricated at temperatures higher than 300 °C.

Fig. 19 shows a 3.65″ IGZO TFT array. The electron mobility is as high as 5 cm2/V-sec, which is 10 times higher than the electron mobility of conventional amorphous-Si TFTs. The sub-threshold slope is 0.6 V/dec, and the on-off ratio is 107. Therefore, the device can be used for high-resolution displays above 300 ppi.

IV. CONCLUSION

Leveraging the in-house expertise in optoelectronics, mechanical engineering, and chemical and material sciences, we developed and, in some cases successfully demonstrated in pilot scale, several important technologies to enable the future generation of flexible displays and electronic components. We reported a novel technology, the FlexUP, to fabricate flexible devices, including displays and sensors, on rigid substrates such as glass and silicon wafers. By inserting a release layer, displays and electronic devices are easily fabricated on flexible substrates, and thereafter, debonded. Atop the flexible substrate, we developed flexible barrier and encapsulation technologies for protecting AMOLEDs from performance-threatening oxygen and moisture infusion. We also attained important advances in two R2R technologies: the plastic support for rewritable e-papers, and a complete R2R process with an ultrathin glass substrate for flexible touch sensors. Our technological advances detailed in this report further illustrate the importance and benefit of working with an interdisciplinary team of scientists and engineers in a multidisciplinary industrial research laboratory such as ITRI. In the future, we fully expect to push these technological advances with our industrial partners to implement these technologies in product-manufacturing environments.

REFERENCES

[1] J. Chung, M. K. Kim, R. Chuang, N. Liu, and C.-P. Chen, "The eco-system build-up and commercialized strategies for Taiwan's flexible display industry," Dept. Ind. Technol., MOEA, Taipei, China, Tech. Rep., 2012.

[2] C. C. Lee, Y. Y. Chang, H. C. Cheng, J. C. Ho, and J. Chen, "A novel approach to make flexible active matrix displays," in *SID Symp. Dig. Tech. Papers*, vol. 54. 2010, pp. 810–813.

[3] J. M. Liu, T. M. Lee, C. H. Wen, and C. M. Leu, "High performance organic-inorganic hybrid plastic substrate for flexible display and electronics," in *SID Symp. Dig. Tech. Papers*, vol. 61. 2010, pp. 913–916.

[4] E. I. Haskal, I. D. French, H. Lifka, R. Sanders, P. T. Kretz, E. Chuiton, G. Gomez, F. Mazel, C. Prat, F. Templier, M. D. Campo, and F. Stahr, "Flexible OLED displays made with the EPLaR process," in *Proc. Eurodisplay*, 2007, pp. 36–39.

[5] I. French, "Flexible e-book," in *SID Symp. Dig. Tech. Papers*, 2009, pp. 100–103.

[6] J. W. Shiu, W. W. Chiu, C. C. Tsai, C. Y. Huang, and J. Chen, "Recent advances in flexible displays of e-paper application," in *Proc. IDW*, 2010, pp. 447–450.

[7] J. W. Shiu, K. C. Lee, C. C. Liang, Y. C. Liao, C. C. Tsai, and J. Chen, "A rugged display: Recent results of flexible cholesteric liquid-crystal displays," *J. Soc. Inf. Display*, vol. 17, no. 10, pp. 811–820, 2009.

[8] P. W. Liu, C. C. Tsai, C. H. Lee, W. H. Huang, and C. W. Chen, "Large area black/white bistable cholesteric liquid crystal display and the thermal-addressing system," in *SID Symp. Dig.*, 2010, pp. 1663–1666.

[9] J. Chen, J. W. Shiu, W. W. Chiu, C. C. Tsai, and C. Y. Huang, "Roll-to-roll flexible display for e-paper applications," in *SID Symp. Dig.*, 2011, pp. 107–110.

[10] J. Geng, C. Dong, L. Zhang, Z. Ma, L. Shi, H. Cao, and H. Yang, "Electrically addressed and thermally erased cholesteric cells," *Appl. Phys. Lett.*, vol. 89, no. 8, pp. 081130-1–081130-3, 2006.

[11] H. Melchior, F. J. Kahn, D. Maydan, and D. B. Fraser, "Thermally addressed electrically erased high-resolution liquid-crystal light valves," *Appl. Phys. Lett.*, vol. 21, no. 8, pp. 392–394, 1972.

[12] S. Huang, J. Shih, A. Wei, M. C. Lin, C. S. Huang, H. T. Lin, C. L. Lin, S. Y. Chang, C. T. Wang, J. Shen, C. H. Hsiao, S. T. Lu, J. Hu, and C. T. Liu, "Roll-to-roll device fabrication on flexible glass web," in *Proc. Assoc. Int. Metall. Coaters Laminators*, 2012.

[13] S. Huang, J. Shih, A. Wei, M. C. Lin, C. S. Huang, H. T. Lin, C. L. Lin, S. Y. Chang, C. T. Wang, J. Shen, C. H. Hsiao, S. T. Lu, J. Hu, and C. T. Liu, "Ultra-slim flexible glass for display and flexible electronic applications," in *Proc. Int. Conf. Food Process Eng.*, 2012.

[14] S. Huang, J. Shih, A. Wei, M. C. Lin, C. S. Huang, H. T. Lin, C. L. Lin, S. Y. Chang, C. T. Wang, J. Shen, C. H. Hsiao, S. T. Lu, J. Hu, and C. T. Liu, "Ultra-slim flexible glass for electronic applications," in *Proc. MRS Fall Meeting Exhibit.*, 2012.

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