Displays develop a new flexibility

Flexible displays are of great interest especially for mobile applications. Currently, there are no active-matrix flexible displays on the market, even though research has been carried out continuously over several years. Here, we introduce flexible displays and the prototype devices that have been developed. Organic thin-film transistors have been fabricated on plastic substrates for display backplanes. We describe the performance of our transistors made using a self-organization process. Finally, a set of research goals are outlined.

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A schematic of an active-matrix (AM) display on a flexible substrate is shown in Fig. 1. The most common type of AM is a thin-film transistor (TFT) array, and the two terms can be used interchangeably. The TFT array is also called a backplane, and is built on a plastic substrate. Display materials, such as electrophoretic displays (EPDs), liquid crystal displays (LCDs), and organic light-emitting diodes (OLEDs), are added on top. A driving voltage is applied at each pixel between the backplane and the common electrode on top.

The TFT-LCDs currently used for notebook or PC monitors and digital TVs mostly use amorphous Si (a-Si) backplanes. High-resolution LCDs in mobile phones, personal digital assistants (PDAs), and some small-screen laptops use low-temperature polycrystalline Si (LTPS) arrays. Organic TFTs (OTFTs) are not currently used in display manufacturing, but are being intensively studied to solve technical issues associated with the use of organic semiconductors.

AM-OLEDs on glass were commercialized in 2003 for a digital still camera (DSC) by SK Display, a joint venture between Sanyo and Kodak. A second product for PDAs was commercialized by Sony in 2004. But so far, no product has reached the market with an AM-LCD or AM-OLED display on a flexible substrate.

Prototype flexible displays

Research into display devices on flexible substrates has focused on backplanes made of a-Si, polycrystalline Si (poly-Si), and OTFTs, with EPDs, LCDs, and OLEDs as the main display elements.

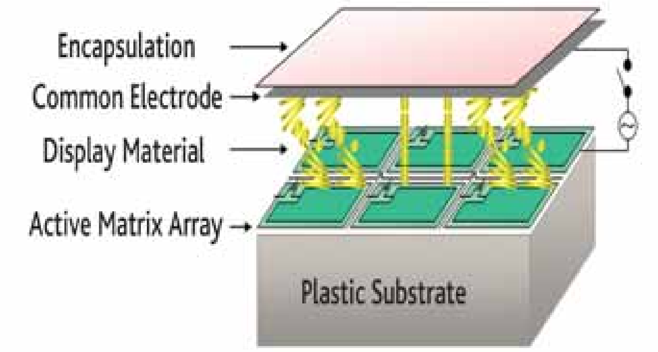

Fig. 1 Schematic of an AM display on plastic.

ISSN:1369 7021 © Elsevier Ltd 2006

Table 1 EPDs on plastic substrates

Company	Display specification	Electrophoretic material	TFT
Philips/E ink[1]	3.5 cm x 3.5 cm 64 x 64 pixels Plastic substrate Radius of curvature ~1 cm Monochrome	E ink	OTFT
Polymer Vision[2] (2005)	5” QVGA 320 x 240 pixels Plastic substrate Monochrome	E ink	OTFT
Polymer Vision/Philips[3]4.7” QVGA (2005)	85 ppi, 320 x 240 pixels Plastic substrate (PEN) Radius of curvature ~7.5 mm Thickness 100 μm, weight 1.6 g Monochrome	E ink	OTFT
E ink/Plastic Logic[4] (2005)	50 mm x 350 mm 100 ppi Plastic substrate Radius of curvature ~3 mm Monochrome	E ink	OTFT
Bridgestone[5] (2004)	3.1” 160 x 160 pixels Plastic substrate Radius of curvature ~20 mm Monochrome	QR-LPD	Passive matrix
Sony[6]	6” Sony LIBRIé e-book readerE ink 170 ppi, 800 x 600 pixels Thickness 13 mm, weight 190 g Monochrome	a-Si	
E-ink/Seiko Epson[7] (2005)	40 mm x 30 mm 200 ppi, 320 x 240 pixels Plastic substrate SUFTLA process Thickness 375 μm, weight 1.2 g Monochrome	E ink	poly-Si

Table 1 summarizes the EPDs developed in the last few years. Most of them use electrophoretic material developed by E Ink, but the TFT can be made of a-Si, poly-Si, or an organic semiconductor. There is one exception to the use of E Ink’s technology. Bridgestone has developed an electrophoretic material that has a fast response time but needs a high driving voltage.

Philips[1], Polymer Vision[2,3], and Plastic Logic[4] have each developed EPDs based on a pentacene OTFT array assembled on a plastic substrate. In collaboration with E Ink, the Philips’ process laminates electronic ink to the plastic sheet, aligning the display pixels with spin-coated pentacene transistors[1]. The resulting EPD of 64 x 64 pixels is 3.5 cm x 3.5 cm in size and rollable to a radius of ~1 cm. The 5” quarter-video-graphics array (QVGA or 320 x 240 pixels) display developed by Polymer Vision[2] provides paper-like viewing comfort with a high contrast ratio for text, graphics, and electronic maps. A display developed by Philips and Polymer Vision is repeatably bendable (over 30 000 times)[3] to a radius of 7.5 mm. The electronic paper (e-paper) display driven by an OTFT backplane on plastic shown in Fig. 2 was developed by Plastic Logic[4]. Solution-based, direct-write inkjet printing and laser patterning were used to produce AM polymer TFT arrays on a polyethylene terephthalate (PET) substrate. The display, which is 350 mm x 350 mm, can be bent to a radius of curvature of 3 mm.

The paper-like display developed by Bridgestone[5] can be as thin as 290 μm. It has 160 x 160 array pixels, a 3.1” diagonal size, and a white-paper-like appearance. A 120 μm thick plastic substrate was used, resulting in a flexible display that can be bent to a 20 mm radius

Fig. 2 EPD fabricated by Plastic Logic.

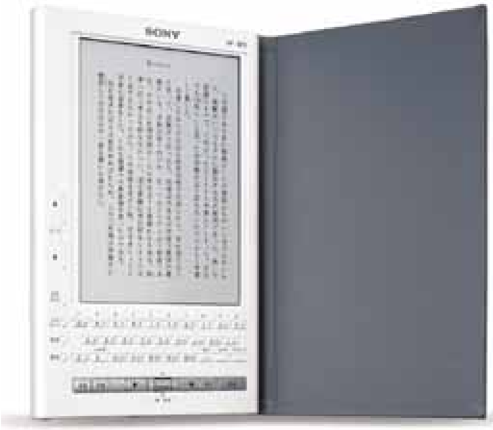

Fig. 3 Sony e-book reader.

Table 2 TFT-LCDs on plastic substrates

Company	Display specification	TFT
Sharp[8] (2002)	4″ reflective color TFT-LCD 85 ppi, 240 x RGB x 240 pixels Aperture ratio 92% PI substrate	a-Si
Samsung Electronics[9] (2005)	5″ transmissive color TFT-LCD 100 ppi, 400 x RGB x 300 pixels PES substrate Thickness 1.2 mm, weight 22 g	a-Si
Seiko-Epson[10] (2001)	0.7″ QVGA 428 x 328 pixels SUFTLA process	poly-Si
Sony[11] (2003)	3.8″ reflective color LCD 320 x RGB x 240 pixels PET substrate	poly-Si
Toshiba[12] (2002)	8.4″ SVGA color TFT-LCD Thickness 0.4 mm, weight 20 g	LTPS

Table 3 Flexible AM-OLEDs

Company	Display specification	TFT
Pioneer[13] (2003)	3″ color OLED 160 x RGB x 120 pixels 256 gray scale (8 bit) Plastic substrate Thickness 0.2 mm, weight 3 g Brightness 70 cd/m^2 at 9 V	Passive matrix
Universal Display/ Vitex[14] (2003)	80 ppi, 64 x 64 pixels PET substrate Brightness 70 cd/m^2 Monochrome	Passive matrix
Seiko-Epson[15] (2003)	2.1″ color AM-OLED 200 x RGB x 150 pixels SUFTLA process Thickness 0.7 mm, weight 3.2 g	poly-Si
Kyung Hee University & Samsung SDI[16] (2005)	4.1″ AM-OLED 65 ppi, 100 x 246 pixels Metal foil substrate Aperture ratio 33%	poly-Si

of curvature. In particular, the response speed of the EPD is sufficiently fast to realize video imaging, even though the display needs a higher driving voltage than those using E Ink material.

Philips, Sony, and E Ink have collaborated to develope the first consumer application of an e-paper display module: the Sony LIBRIé electronic-book (e-book) reader (Fig. 3)[6]. This technology makes the e-book light and highly portable, measuring only 126 mm x 190 mm x 13 mm and weighing approximately 190 g.

Seiko-Epson and E ink have also developed a flexible AM-EPD aimed at e-paper applications. A surface free technology by laser ablation/annealing (SUFTLA) process is used to transfer LTPS-TFTs originally manufactured on glass onto a plastic substrate. A microencapsulated electrophoretic material is then added to realize a flexible 2″ QVGA AM-EPD panel[7].

Because of their reflective mode, EPDs can, in the main, only be used for e-paper or e-books. In addition, EPDs cannot be used for full-color video displays. Therefore, LCDs and OLEDs are gaining more attention for flexible displays.

Prototype flexible TFT-LCDs and AM-OLEDs developed by different companies are summarized in Tables 2 and 3, respectively. Sharp has

Fig. 4 Full-color TFT-LCD on PES by Samsung Electronics.

developed a reflective-type color TFT-LCD on a polyimide (PI) substrate[8]. It has a 4" diagonal display area with 240 × RGB × 240 pixels (i.e. 85 ppi) using an a-Si TFT backplane. Note that PI is not transparent, so it is not suitable for transmissive TFT-LCDs. On the other hand, Samsung Electronics has used a polyethersulfone (PES) substrate with an a-Si backplane to make a transmission-type 7" TFT-LCD, which can be used in TV and monitor applications (Fig. 4)[9]. The resolution is 480 x 640 pixels and the display features a response time of 35 ms and a brightness of 120 nit (1 nit is roughly equal to the brightness of a standard candle).

As well as using the SUFTLA process to manufacture an AM-EPD (see above), Seiko-Epson has also used the technology to transfer a LTPS TFT backplane from glass to a plastic substrate before carrying out a liquid-crystal process to make a plastic TFT-LCD[10]. Another transfer technology has been developed by Sony to fabricate an all-plastic, 3.8" reflective color LTPS TFT-LCD[11]. The transfer process does not significantly damage the device layer. Toshiba has taken an alternative approach by building a flexible TFT-LCD on very thin glass[12]. The full-color, 8.4" LTPS TFT-LCD supports super-video-graphics array (SVGA or 600 x 800 pixels) resolution.

Plastic TFT-LCDs have the great advantage of mature LCD manufacturing technology. However, flexing the displays can lead to stability problems because the end seal at the periphery of the LCD can easily breakdown and rolling and bending can make the cell gap unstable. The polarizers used on either side of the LCD are also a big drawback in making thin and bendable displays. These factors have led to interest in using OLED displays (Table 3).

Pioneer has developed a 3", 160 x 120 pixels, passive-matrix (PM) OLED on a plastic substrate[13]. With a brightness of 70 cd/m^2 at 9 V, the display is 0.2 mm thick and weighs 3 g. Universal Display Corporation (UDC) has also manufactured a video-rate PM-OLED display on a flexible plastic substrate[14]. Multilayer barrier encapsulation technology is used to protect the device from moisture and oxygen absorption. The flexible display is based on highly efficient electrophosphorescent OLEDs deposited on a barrier-coated plastic film, which is then sealed with an optically transmissive multilayer barrier coating.

A color AM-OLED display has been fabricated by Seiko-Epson on a plastic substrate, again using SUFTLA technology[15]. After the LTPS-TFT backplane is transferred to a plastic substrate, a color OLED display is assembled on top using an inkjet printing technique.

Kyung Hee University in Korea and Samsung SDI have developed a 4.1" AM-OLED display with a top-emission structure on flexible stainless steel foil (Fig. 5)[16]. This approach has the advantage of being able to use a higher process temperature because the stainless steel foil can be heated up to 900°C. Increasing the process temperature improves the quality of the poly-Si in the TFT backplane.

OLEDs offer the opportunity to develop the best flexible displays because they can be very thin and consist entirely of solid-state materials. However, thin-film encapsulation is required in manufacturing to prevent degradation of the OLEDs, which are very sensitive to water vapor and oxygen absorption.

Table 4 summarizes the flexible LCD and OLED displays that have been made using OTFT backplanes rather than a-Si or poly-Si arrays. NHK has developed pentacene OTFT technology on plastic substrates and applied it to make polymer-dispersed LCD[17] and AM-OLED[18] displays. The Industrial Technology Research Institute (ITRI) in Taiwan has made a TFT-LCD on plastic that is driven by OTFTs[19]. However, the quality of these displays based on OTFTs is not very good. Therefore, research is being carried out to develop high-quality, OTFT displays.

OTFTs on plastic substrates

Recently, the number of publications on OTFTs has increased because of their potential applications in flexible displays and cheap electronic circuits such as radio-frequency identification tags. OTFTs fabricated on plastic substrates, such as polyethylene naphthalate (PEN), polyester, PET, PI, and polycarbonate, and their properties, such as the field-effect mobility, threshold voltage (V_T), gate voltage swing (S), and on/off current ratio, are depicted in Table 5[20-34].

Table 4. Flexible displays based on OTFT backplanes

Company	Display specification	TFT
NHK[17] (2005)	2" polymer-dispersed LCD 2 mm x 2 mm, 16 x 16 pixels Plastic substrate	OTFT
NHK[18] (2004)	AM-OLED 4 x 4 pixels Polycarbonate substrate	OTFT
ITRI[19] (2004)	3" TFT-LCD 64 x 128 pixels	OTFT

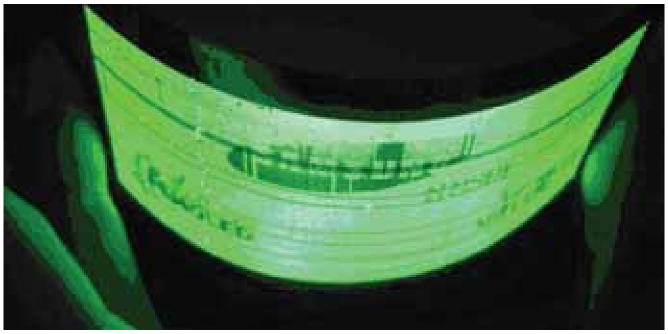

Fig. 5 Flexible AM-OLED on a metal foil substrate developed by Kyung Hee University and Samsung SDI.

Most OTFTs use pentacene thin films. Pentacene OTFTs fabricated by vacuum evaporation[20,22-25,28,29] have field-effect mobilities in the range 0.2~1.2 cm^2/Vs and on/off current ratios from 10^2 to 10^8. Ring oscillators have been made on plastic using *p*-type[20,24,33] and complementary metal-oxide semiconductor (CMOS) circuits[32]. Here, the maximum field-effect mobility and on/off current ratios are 1.2 cm^2/Vs and 10^8, respectively[23].

OTFTs with pentacene deposited from solution have field-effect mobilities of ~0.02 cm^2/Vs[27]. On the other hand, a polymer TFT using poly(3-hexylthiophene) or P3HT[34] exhibits a mobility of 0.086 cm^2/Vs and on/off current ratio of 10^4. The performance of solution-processed OTFTs, therefore, is inferior to those processed in a vacuum, with mobilities about two orders of magnitude lower. However, cost can be greatly reduced by using printing processes, so that this remains an area of significant research. OTFTs based on solutions of small molecules or polymer TFTs using polymer semiconductors with thiophene groups are being intensively studied to improve performance and stability.

OTFT fabrication using a self-organization process

In the case of an a-Si or poly-Si TFT array, photolithography techniques are used to pattern the thin-film Si layer, as well as source/drain and bus lines. However, with organic semiconductors, there is significant degradation in TFT performance after photoresist patterning because the organic layer is damaged during the process. Therefore, shadow-mask techniques are widely used, although this method cannot produce high-resolution displays. TFT backplanes can be made by printing the organic semiconductors, but the performance, especially field-effect mobility, is much poorer than for devices fabricated using a vacuum process. We have developed a technique that allows pentacene to be selectively grown on the TFT area and not the pixel area by using a self-organization process. This gives pentacene islands for TFTs and results in a high-performance device.

Fig. 6 shows a cross-sectional view of the bottom-contact OTFT device we have manufactured. The first fabrication step is the deposition of a gas barrier on a PES substrate. We add a 100 nm thick SiN$_x$ layer on both sides of the substrate by plasma-enhanced chemical vapor deposition (PECVD). Al is used as a gate bus line because it facilitates easy etching and is flexible. Cross-linked poly(vinyl pyrrolidone), or PVP, is then spin coated and cured in a vacuum oven to give a 450 μm thick gate insulator layer[35,36]. Organic gate insulators are preferred for flexible devices because they reduce the stress between the TFT layers and the organic substrate[37]. The source and drain contacts are then needed for the bottom-contact structure. The

Table 5 OTFTs on plastic substrates for displays

Organic semiconductor	Substrate	Mobility (cm^2/Vs)	V_T (V)	S (V/dec)	I_{on}/I_{off}	Note
Pentacene	PEN	0.3	+2	1.2	10^6	Five-stages ring oscillator[20]
Pentacene	PEN	0.05	-4	5	10^3	All-organic TFT[21]
Pentacene	PEN	0.3	NR	NR	10^5	Bending experiment[22]
Pentacene	PEN	1.2	NR	NR	10^8	Polymer-dispersed LCD[23]
Pentacene	Polyester	0.45	+3.2	NR	NR	Five-stages ring oscillator[24]
Pentacene	PET	0.24	~ -7	NR	10^4	Transparent OTFT with NiO$_x$ S/D electrodes[25]
Pentacene	PI	0.02	-1.7	NR	10^2	All-organic TFT[26]
Pentacene	PI	0.02	NR	NR	10^6	E ink shift register soluble pentacene[27]
Pentacene	PI	0.5	NR	NR	10^5	Bending radius less than 1 mm with sandwich structure[28]
Pentacene	PI	0.2	NR	NR	10^7	VT control with double gate structures[29]
Pentacene	Polycarbonate	0.49	-1.8	NR	10^4	AM-OLED[30]
Pentacene	Paper	0.2	NR	1.8	10^6	Ring oscillator on paper[31]
Pentacene,	PEN	0.1	NR	0.6	10^4	CMOS ring oscillator[32]
F_{16}CuPc		0.002	NR	1.4	10^3	
P3HT	Polyester	0.02	+3	NR	NR	Seven-stages ring oscillator[33]
P3HT	Paper	0.086	-11.9	NR	10^4	Parylene-coated paper substrate[34]

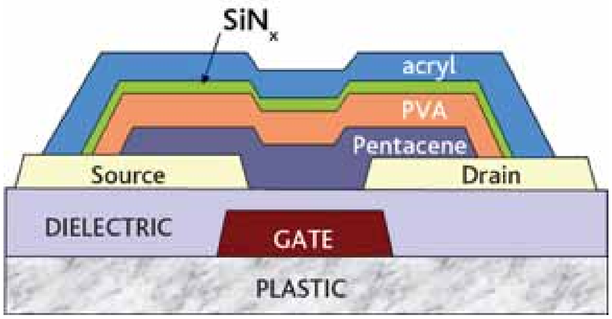

Fig. 6 Cross-section of a pentacene OTFT.

high work function of Au is used to give an ohmic contact with *p*-type pentacene. A very thin layer of Cr (5 nm) is also used for adhesion to the PVP gate insulator. Next, the pentacene layer is deposited on the gate insulator using organic vapor deposition (OVD). Here, the organic compound is thermally evaporated and then transported in a hot-walled reactor by an inert carrier gas to a cooled substrate where condensation occurs[38]. Pentacene on the gate insulator is a polycrystalline material, and grain size, grain orientation, and surface morphology are important parameters in determining TFT performance. By optimizing the growth conditions, better films can be achieved. A film grown at 180°C at the pressure of 2 torr on a self-assembled monolayer (SAM) of octadecyltrichlorosilane (OTS) has a grain size of ~20 μm. The scanning electron micrograph in Fig. 7 shows the effect of the SAM by comparing pentacene films grown on PES with and without the OTS monolayer. OTS treatment results in a much larger grain size and less distinct grain boundaries.

When pentacene is deposited on the heated substrate, it can migrate from a hydrophobic to a hydrophilic surface. If the backplane array is divided into TFT regions with a hydrophobic surface and pixel regions with a hydrophilic surface, pentacene is deposited only on the TFT regions[37]. Fig. 8 shows some display pixels before and after pentacene growth via this self-organization process. The TFT areas are black because they are covered with pentacene. There is no deposition of pentacene on the pixel area.

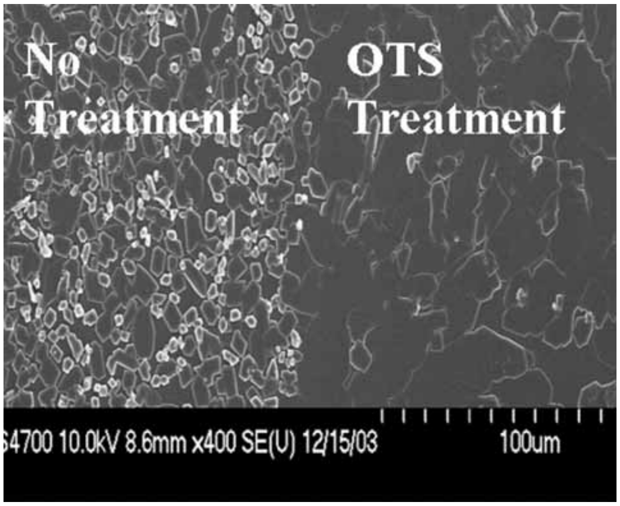

Fig. 7 Surface morphology of a pentacene film grown on cross-linked PVP without (left) and with (right) OTS treatment.

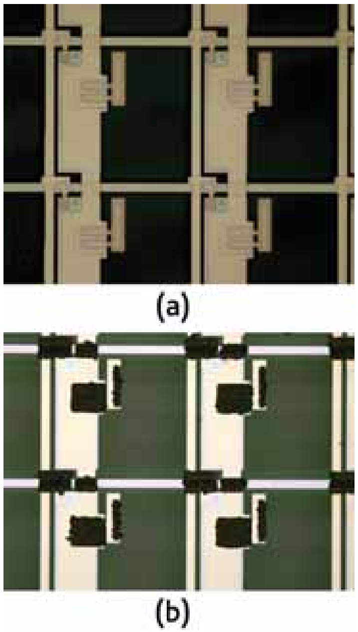

Fig. 8 Top views of the pixels for an AM-OLED display before (top) and after (below) self-organized pentacene growth.

Semiconductor devices are passivated with suitable insulators like SiN$_x$, SiO$_2$, or an organic insulator. OTFTs also need to be passivated with an insulator. However, organic semiconductors have a weak structure compared with inorganic materials, so that they can be easily damaged physically or chemically during the passivation process. Such damage is significant in the degradation of TFT performance.

Most OTFTs are passivated by polyvinylalcohol (PVA) because of its aqueous solubility. We have used PVA as a first passivation step, followed by photoacryl as a second layer. This can reduce the water vapor transmission rate[39] and, therefore, degradation of the OTFT. On the top of the organic layer of PVA and photoacryl, SiN$_x$ is deposited to reduce water vapor and oxygen transmission rates even further.

Table 6 shows the performance of OTFTs before and after passivation. The on-currents are almost the same after passivation because of the changes in mobility and threshold voltage. The

Table 6 Performance of pentacene OTFTs fabricated on a PES substrate using a self-organization process before and after passivation.

Fabrication step	Mobility (cm^2/Vs)	V_T (V)	S (V/dec)	I_{on}/I_{off}
Before passivation	1.1	-7	1.6	10^9
After PVA	0.95	-11.5	2.0	10^5
After photoacryl	0.5	-10.5	1.3	10^7

threshold voltage shift compensates the drop in mobility after passivation[39]. The lifetime, defined as the time in which the on-current drops by half, is ~11 000 hours in ambient air. If we add an inorganic passivation layer like SiN_x, the lifetime can be further extended.

OTFTs can be unstable under electrical stress or thermal annealing at modest temperatures of 150°C. However, we have confirmed that electrical stress can be ameliorated by optimizing the gate insulator so that there is no defect creation under the gate-bias stress[40]. Furthermore, the Someya group at the University of Tokyo has confirmed that pentacene OTFT performance can be very stable after prolonged annealing at 150°C[41]. We conclude, therefore, that OTFT backplanes can be used for the manufacturing of flexible displays in the future because there is no fundamental limit to the lifetime. However, to extend the lifetime of devices, protecting the organic semiconductor from water vapor and oxygen is of prime importance.

Future research goals

The most important issue for flexible displays is developing a plastic substrate that can be handled like a glass. This means that most of the properties of the plastic, such as the glass transition temperature, thermal expansion coefficient, and gas absorption ratio, should be similar to glass. However, this will be almost impossible to achieve in the near future. Therefore, using gas barriers and thin-film encapsulation are the only solution for manufacturing flexible displays.

The performance of OTFTs is now good enough for them to be used in the manufacturing of displays because the on-current is higher than 1 μA and the on/off current ratio is higher than 10^6. The lifetime of OTFTs, associated with thermal, chemical, and electrical stability, is a critical issue. The use of OTFT backplanes with LCDs and OLEDs is at a very early stage, and no high-quality display prototypes have yet been developed. Therefore, the integration of the OTFT backplane with the display mode is being studied in order to develop flexible displays with similar performances to the current TFT-LCDs on the market.

The flexibility of displays under rolling and bending is another important topic, and it is dependent on the substrate thickness, device structure, device materials, substrate material, passivation layers, and so on. Light-induced leakage currents in OTFTs[42] can also degrade the display quality, which can be an issue in making high-quality displays. mt

Acknowledgments

This work was supported by a grant (F0004082) from the Information Display R&D Center, one of the 21st Century Frontier R&D Programs funded by the Ministry of Commerce, Industry, and Energy of the Korean Government.

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