Flexible Displays: Attributes, Technologies Compatible with Flexible Substrates, and Applications

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Abstract

Flexible displays are an exciting development because of their physical and performance attributes and their capability to enable new products requiring displays with unique form factors that the current rigid glass substrate-based displays cannot support. Flexible displays can be very thin and lightweight, have unique form factors, and be highly rugged and not prone to breakage on impact unlike rigid and flat glass substrate-based displays. The flexible form factors such as having an arbitrary shape, ability to be curved, conformal,

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bendable, foldable, and rollable can enable a variety of new applications and products. In this chapter, we will discuss the various attributes of the flexible displays, their potential applications, and the display media appropriate for flexible displays.

Keywords

Bendable displays • Bendable OLED display • Conformal display application • In wrist watch • Conformal display surface • Display media technologies • Comparison of • Electrophoretic display (EPD) media • LCD media • OLED display media • Electrophoretic display (EPD) media • Flat display surface • Flexible displays • Applications • Cost attributes • Development • Display media technologies • Performance attributes • Physical attributes • Plastic substrates • Foldable display • Foldable electrophoretic display • OLED display media • Rollable display • Rollable displays

Acronyms

AM EPD	Active matrix electrophoretic display
AM LCD	Active matrix liquid crystal display
AM OLED	Active matrix organic light emitting diode
EPD	Electrophoretic display
LCD	Liquid crystal display
MEMS	Micro electro-mechanical systems
OLED	Organic light emitting diode
OTFT	Organic thin film transistor
RTR	Roll to roll

Introduction

During the past three decades, development of flat panel displays, more particularly active matrix flat panel displays based on rigid and flat glass substrates, has had a profound impact on the society by enabling creation of low-power displays for mobile applications (communications) such as mobile phones and notebook PCs and by replacing the CRT displays that are bulky, heavy, and power hungry for the desktop PC and home TV applications. Glass substrate-based flat panel displays such as AM LCDs have enabled so many new applications for which the venerable CRT displays were just not suitable. Flexible displays are viewed to be the next big frontier for the display technology development.

There has been much interest in flexible displays and electronics fabricated using thin flexible plastic substrates for a long time, because of their perceived potential advantages compared to conventional displays built on rigid glass substrates. The potential advantages for flexible displays include being very thin, lightweight, highly rugged with greatly minimized propensity for breakage, and amenable to low-cost roll-to-roll manufacturing, in comparison to devices built on the conventional rigid glass substrates. In addition, flexible electronics and displays can enable a variety of new applications due to their ability to have unique form factors and to be curved and conformable. Further flexible displays can be rollable or foldable when not in use during storage or transportation.

While there have been interest and activities in the development of rugged plastic substrate-based LCDs for more than 25 years, interest in development of flexible displays intensified during the latter half of this period because of the significant advances in the enabling technologies for flexible displays and the R&D investments in flexible display developments have grown substantially. At the time of this writing, flexible substrate-based display technologies, such as OLEDs built on flexible plastic substrates, are already commercialized for use in premium performance smartphones and wrist watches with a rigid configuration. While the ultimate vision of a flexible display is one where it is foldable and rollable numerous times during use and during transportation and storage, the initial applications are focused on taking advantage of their thinness, form factor, weight savings, low power, and ruggedness attributes. Recent market studies (http://www.idtechex.com/research/reports/oled-display-forecast-2015-2025-the-rise-of-plastic-and-flexible-displays-000426.asp) project that the market for plastic and flexible AM OLED displays will rise to US $16B per year by the year 2020.

In this chapter, we will first discuss the physical, performance, and cost attributes of the flexible displays being developed. We will then discuss the display media technologies compatible with flexible displays. Finally, we will discuss the various potential applications for flexible displays. The detailed technical aspects of flexible substrates and flexible display fabrication are discussed in chapter "▶ Flexible Displays: Substrate and TFT Technology Options and Processing Strategies" of this handbook.

Physical Attributes

The physical attributes include thickness, weight, form factor, ruggedness, and flexibility with the ability to be flat, conformal, bent, folded, and rolled into a tube for storage and transportation when not in use.

Compared to the rigid glass substrate-based displays, flexible displays are inherently and substantially thinner and lighter weight. Superior size, weight, and power (SWaP) attributes are highly desirable for mobile electronics applications and for a variety of other commercial and aerospace and defense applications. The flat panel display industry has been making steady progress over the past two decades in reducing the thickness of the display glass substrates from ~ 1 to ~ 0.4 mm for mobile display applications, in particular. A flexible display based on a polymer (plastic) substrate can allow a paradigm change in the physical attributes of the display in relation to the rigid glass substrate-based displays. First, flexible displays can be ultrathin (e.g., as thin as ~ 50 μm or 0.05 mm) compared to the thin glass substrate-based mobile displays with thickness in the range of ~ 400 μm or 0.4 mm. Also, with the density of typical plastic substrate being typically about a factor of

2 lower than display glass, a flexible plastic substrate-based display can be ultimately lighter by a factor of ~ 16, compared to a glass substrate-based mobile display.

It is well known that thinner glass substrates and displays made using these substrates are extremely fragile and can shatter and break on impact when dropped on the floor accidentally. Currently, for critical applications, the glass substrate-based displays are ruggedized typically by using a thick impact-resistant cover glass, which is either laminated to the display surface using an adhesive or mechanically fixed in front of the display glass, to protect the actual display against impact stresses. This will increase the display thickness and weight even more. In comparison, displays fabricated on thin flexible substrate materials such as a plastic or stainless steel foils are highly rugged against impact and do not shatter or break.

Capability for having a unique form factor and the ability to be conformal, bent, folded, or rolled is an important attribute of flexible displays. Unlike rigid glass substrates, flexible displays fabricated on thin plastic or metal foil substrates can be cut to any size and shape readily and cost-effectively. Their ability to be conformal to a surface such as the shape of a wrist surface or cuff surface, for example, allows numerous applications in the consumer, industrial, and aerospace and defense applications as discussed in detail in section "Flexible Display Applications." Similarly, flexible displays can be bendable and rollable, and these attributes enable a variety of new and novel products that cannot be imagined using the current rigid glass-based displays. For example, rollable flexible displays with a rolling radius of <5 mm have already been demonstrated (Noda et al. 2010).

While flexible displays can be highly rugged against impact, they can also be very fragile when self- supporting, as they are extremely thin. However, they can be mechanically protected during use, and stowage for transportation and storage when not in use, when they are appropriately integrated into the product for the intended application. For example, a large rollable display would need to be protected by mechanical means in the "rolled-out" condition during use and with an appropriate tubular housing for stowage when transported or stored when not in use.

Performance Attributes

Flexible display performance parameters include:

- Image quality
- Sunlight readability
- Power consumption
- Ruggedness and reformable form factor

The display image quality performance metrics include luminance, color gamut, number of gray levels, gray-level luminance uniformity, dynamic luminance range, viewing angle, and video performance. The image quality of flexible displays built on flexible foil substrates is expected to be similar to the image quality of conventional flat panel displays built on flat and rigid glass substrates, as it is primarily determined by the display media used and not on the substrate material. Mobile electronic devices are one of the important target applications for flexible displays. As mobile electronic devices are battery powered and used in a wide range of ambient lighting conditions, the displays need to be sunlight readable and consume less power. Similar to the image quality metrics, power consumption depends on the display media utilized and not on the substrate. Techniques for making the conventional flat panel displays sunlight readable, namely, reducing the reflection from the display and increasing the display luminance, can also be employed for flexible displays.

The most important distinguishing performance attributes of flexible displays are the inherent ruggedness against impact stresses and the ability to be reformable, for example, bendable during use, or foldable or rollable for stowage. These two attributes enable a variety of new applications that cannot be served by the conventional rigid glass substrate-based displays.

Cost Attributes

While the physical and performance attributes of the flexible displays are the primary reason for the current high level of interest in flexible displays, the other reason of the potential for low cost is not lost from consideration for companies developing flexible display technologies. Flexible displays fabricated using thin flexible plastic substrates or metal foil substrates are amenable for low-cost roll-to-roll (RTR) processing. RTR technologies are currently utilized in the manufacture of various thin films and thin film device products cost- efficiently. Fabrication of flexible displays by direct printing of row and column address buses, thin film transistor (TFT) switching devices, and the display pixels using an RTR manufacturing method is believed to have the ultimate low-cost potential. While important progress continues to be made on this ultimate vision for flexible display manufacturing, some flexible display developers are currently pursuing implementing some aspects of RTR process in their flexible display fabrication processes to start benefiting from the high-productivity and low-cost aspects of the RTR processes. Also, while the ultimate vision for a flexible display is a flexible AM OLED (because of its superior display performance attributes) with its highly demanding TFT backplane requirements and the barrier layer (for oxygen and water vapor) requirements, there are many flexible display applications that do not require a TFT backplane or have stringent barrier layer requirements. Examples of these displays include flexible displays for low-power electronic shelf labels and large area signage using bistable reflective display media such as EPD and cholesteric LCD, which can be addressed by passive matrix. RTR technologies for manufacturing these types of flexible displays are being commercialized.

Display Media Technologies

For active matrix flexible displays, the popular display media being considered include liquid crystal display (LCD), electrophoretic display (EPD), and organic light emitting diode (OLED) display. These display media also happen to be the most popular ones in

Table 1 Comparison of display media technologies

Attribute	LCD		EPD	OLED
	Transmissive/ transflective	REflective (cholesteric)		
Flexibility	OK	OK	Better	Best
Ruggedness	OK	OK	Better	Best
Image quality	Better	OK	OK	Best
Power consumption	Ok	Best	Best	OK
Response time	OK	Poor	Poor	Best
Issues	1. Flexible backlight needed 2. Sensitive to cell gap changes	1. Front lighting needed for dark ambient viewing 2. Sensitive to cell gap changes	1. Front lighting needed for dark ambient viewing	1. Flexible gas permission barrier film needed

use or under active development using flat rigid glass substrates. Science and technology of these display media, as used with conventional display glass substrates, is discussed in detail in Sects. 6, "Emissive Displays," 7, "Liquid Crystal Displays," and 8, "Paper-like and Low Power Displays" of this handbook. In the following, we will discuss the applicability of these display media for use with flexible substrate and display application. Table 1 shows the relative comparison of the flexible display attributes using these display media. Some of the emerging display media such as electrowetting (Feenstra et al. 2010) and MEMS (http://www.mirasoldisplays.com/) have a potential for being used in flexible display applications because of their unique advantages. However, we will not discuss them further in this chapter.

LCD Media

One of the significant issues with the use of LCD media for flexible displays is the LC (liquid crystal) cell gap control. LC cell gap value has a significant effect on the display optical performance (luminance, contrast ratio, chromaticity stability, viewing angle, etc.), and maintaining this cell gap at its optimum value as the display is bent or flexed is difficult. Nevertheless, LCD can be a good display media if the objective of the flexible (plastic or metal foil based) display is thin, lightweight, and rugged and close to being flat without any significant level of bending. Secondly, the typical transmissive LCD mode displays that are widely in use today for a broad range of applications require a backlight that needs to be flexible (Montgomery et al. 2009) and a color filter array that needs to be fabricated on a flexible substrate. Low-power reflective LCD mode displays do not require a backlight. However, they do need to be front light, for dark ambient night time viewing, thereby requiring a front lighting scheme that is compatible with the flexible form factor of the display surface involved.

Cholesteric mode LCDs (Khan et al. 2006; Montbach et al. 2009; Kent Displays Inc; Chen et al. 2009; Kato et al. 2010) are being developed for the flexible electronic paper applications, in addition to a variety of other applications including shelf label displays, e-skins, and outdoor advertisement displays. They are bistable and do not require any power in high ambient light conditions, except when updating the image on the display, and thus have the ultimate low-power potential. However, they have slow switching speeds (~100 ms) and thus are not suitable for video applications. In addition, it is not very easy to achieve full color displays with good color saturation using this technology.

Electrophoretic Display (EPD) Media

EPD (McCreary 2007; Huitema et al. 2009; Burns 2010) is a reflective bistable (low-power) display that does not have the cell gap control issues as in LCDs. It is based on microencapsulated oppositely charged colored particles that move in an electric field. The EPD media are typically fabricated in a film form (electronic-ink film) and are attached to the TFT backplane by hot roll lamination. The film consists of microcapsules in a polymer binder coated onto a substrate with an outer layer of polyester and indium tin oxide that serves as the counter electrode for the pixel electrode in the active matrix display. The pixel is switched by moving the submicron-sized black and white particles in the microcapsules, with opposite charge. Depending on whether white or black submicron-sized particles are closer to the viewer, light is scattered back (white state) or absorbed (black state). As the EPD media is bistable, grayscale is achieved by pulse width modulation. In recent times, significant advances are made in the EPD technology in reducing the drive voltages and improving the response time. As this is a reflective mode display, it has excellent sunlight viewability characteristics. As the barrier layer requirements for protection of the EPD media and the requirements of the layer for protection of the EPD media and the requirements of the active matrix TFT backplane for driving the EPD are not stringent, and the simplicity of the monochrome reflective, bistable EPD technology, there is interest in commercializing flexible displays using this display media, for applications such as e-books and a variety of other applications. However, response time in the present practical devices is still in the ~100 ms range and does not support full motion video applications, and additional development is needed for realizing full color EPDs.

OLED Display Media

AM OLED (active matrix organic light emitting diode) display technology offers significant advantages over the current well-entrenched AM LCD with respect to superior image quality with wide-viewing angle and fast response time and being lighter and thinner, low in cost (does not need backlight or color filters), and low in power. Because of this, many companies are actively developing AM OLED displays built using rigid flat glass substrates. These rigid glass substrate-based AM OLED displays are now commercialized for use in premium performance smartphones, tablet PCs, and large screen TVs. Commercialization of plastic substrate-based AM OLEDs has also started for use in premium performance smartphones (http://www.gsmarena.com/samsung_galaxy_round_g910s-5766.php; http://www.samsung.com/global/galaxy/galaxys6/galaxy-s6-edge/; http://www.lg.com/us/mobile-phones/gflex2) and wrist watches (http://appleinsider.com/articles/14/09/29/apple-watchs-advanced-amoled-display-far-more-costly-than-traditional-screens—report), even though in a rigid format, to benefit from their thinness, lightweight, and ruggedness. OLED display media are believed to be ideal choice for use in a flexible display as it represents the ultimate flexible display with a rugged solid-state structure along with the other attributes including full color, superior image quality, full motion video, and low power. However, the OLED display media have very stringent requirements both with respect to the barrier layer specifications for moisture and oxygen permeation and the active matrix TFT backplane performance. However, significant progress has been made in the thin film barrier layer technology and active matrix backplane and TFT technologies as discussed in chapter "▶ Flexible Displays: Substrate and TFT Technology Options and Processing Strategies." Recently, significant progress has been made, and impressive flexible AM OLED displays have been demonstrated as discussed in chapter "▶ Flexible Displays: Substrate and TFT Technology Options and Processing Strategies."

Flexible Display Applications

A very broad range of flexible display applications are being envisioned and pursued. On one end of the application spectrum, flexible displays encompass low resolution, direct addressed or passive matrix addressed displays for small electronic shelf labels, and large electronic advertisement displays, while on the end of the spectrum, they encompass active matrix addressed, high-performance, high-resolution, and mobile information displays. Currently, there is a high level of interest in flexible active matrix displays as they enable broad range of new application. Flexible displays offer significant freedom and opportunity to product designers in the design of products utilizing flexible displays due to its unique attributes described in sections "Physical Attributes," "Performance Attributes," and "Cost Attributes." In the following, we will discuss the various categories of applications envisioned for the flexible displays.

Flat Display Surface

As flexible displays fabricated on metal foil or polymer foil substrates that are impact resistant unlike glass, they are being developed for a straightforward replacement for

Fig. 1 Example of a conformal display application in a wrist watch (http://www.samsung.com/us/mobile/wearable-tech/SM-R750AZKAATT)

displays fabricated on conventional glass substrates. In this application, flexible displays enable significant weight and thickness savings in addition to being inherently rugged.

Conformal Display Surface

Flexible displays can enable conformal display applications where the display surface conforms to a specific surface curvature of interest. Figure 1 shows an example of a conformal display on a wrist-worn device (http://www.samsung.com/us/mobile/wearable-tech/SM-R750AZKAATT). Other examples of conformal display applications include displays for cuff-worn devices and displays on various devices with curved surfaces. In these applications, the display is designed to be bent only once during its operation. Examples of this implementation in recent commercial products include curved/conformal AM OLED displays built on thin plastic substrates in Samsung (http://www.gsmarena.com/samsung_galaxy_round_g910s-5766.php; http://www.samsung.com/global/galaxy/galaxys6/galaxy-s6-edge/) and LG (http://www.lg.com/us/mobile-phones/gflex2) smart phones and Apple watch (http://www.samsung.com/global/galaxy/galaxys6/galaxy-s6-edge/).

Bendable Displays

Some applications may require the flexible display to be bent over a desired curvature of interest multiple times, during use, to suit the application requirements. Figure 2 shows example of a bendable display and application (Fischer et al. 2011).

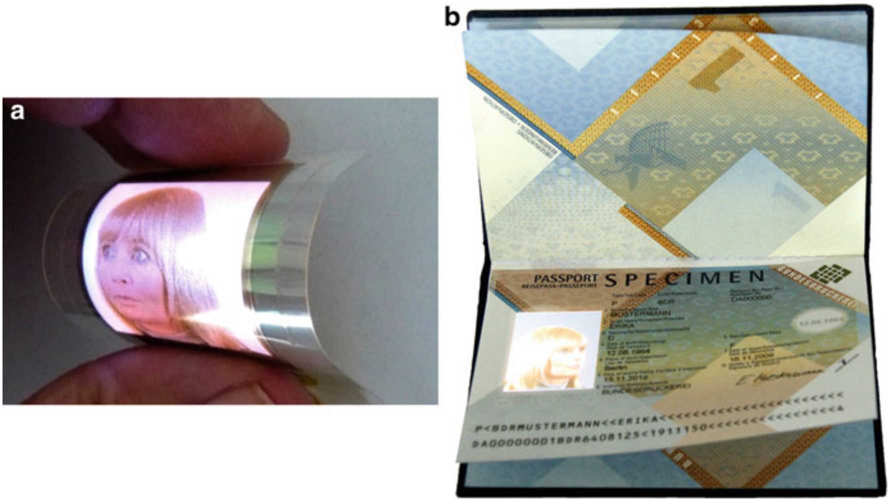

Fig. 2 Example of bendable AM OLED display (**a**) and application in an electronic passport (**b**) (Fischer et al. 2011)

Fig. 3 Example of a foldable electrophoretic display by Polymer Vision (Kato et al. 2010)

Foldable Display

Foldable displays are another category of application. These applications decouple the device size and the display size and allow the display size to much larger than the device size. Figure 3 shows an example of a foldable (and rollable) display, Readius®, using an organic TFT backplane and EPD display media, demonstrated by Polymer Vision (Kato et al. 2010). This type of device involves bending and unbending and rolling and unrolling the flexible display multiple times during the life of the device usage.

Rollable Display

Fully rollable high-performance flexible AM OLED display is the ultimate vision of the flexible display development efforts. Fig. 4a shows a concept device by UDC for

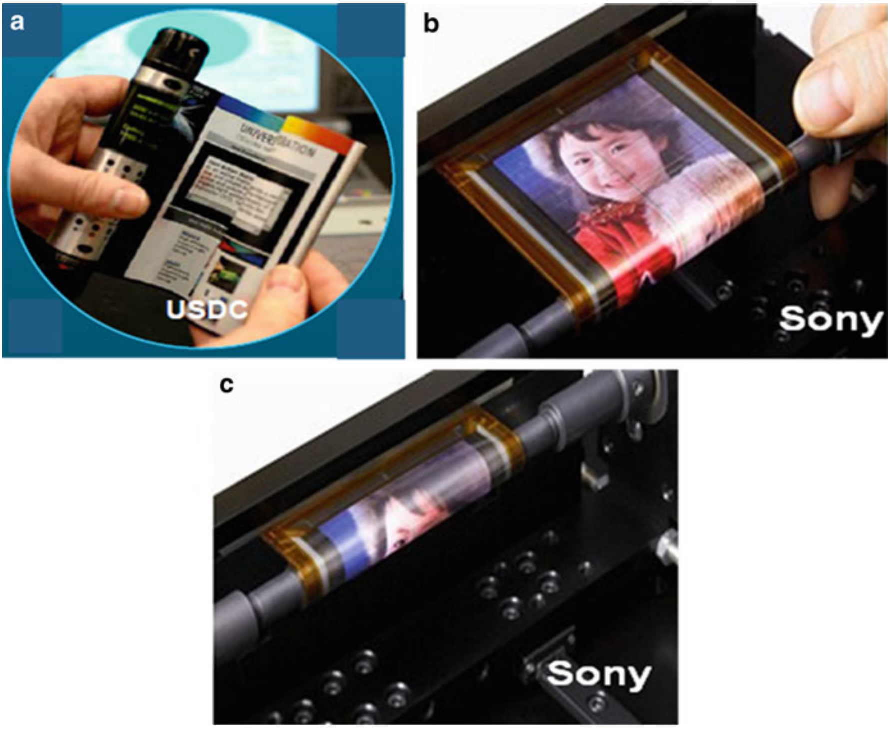

Fig. 4 Examples of rollable displays: (**a**) rollable concept display device, (**b** and **c**) flexible and rollable OLED display fabricated using an organic TFT backplane in the rolled-out and rolled-in condition (Noda et al. 2010)

a rollable, full color flexible AM OLED display. Figure 4b, c shows photographs of a rollable, full color, flexible AM OLED display demonstrated by Sony (Noda et al. 2010). This display utilizes an organic TFT backplane and OLED display media. Rollable displays also allow decoupling of the device size and the display size. The display is rolled in when not in use, for transportation and storage.

Summary and Conclusion

Display has been significant enabler and central to the revolutionary advances in devices, systems, and applications encompassing computers, communications, and entertainment TV, in recent times. During the past two decades, flat panel displays, more particularly the active matrix TFT flat panel displays, have enabled new applications such as notebook PC that would not have been possible without them. The value proposition was compelling for replacing the dominant (and bulky) CRT display with a TFT-LCD with its attributes of being significantly thinner, lighter, and having superior image quality and consuming less power in essentially all of its applications. Having experienced the phenomenal successes in the active matrix flat panel display developments and its widespread adaptation in broad range of applications, the display industry is now fascinated at the prospects of repeating that success with the development of flexible displays. Flexible displays represent a new paradigm in display technology development. First, compared to the rigid flat glass-based displays, flexible displays are significantly lighter, thinner, and more rugged and can be rollable or foldable for stowage. Secondly, they can have unique form factors with respect to size and shape that allows a variety of new applications. In addition, flexible displays have a potential for roll-to-roll (RTR) manufacturing for significant cost reduction.

During the past few years, significant progress has been made in the development of flexible display technology, applications, demonstrators, as well highly successful initial commercial products. Impressive demonstrations have been shown for the flexible AM OLED displays. Flexible AM OLEDs (built on thin plastic foil substrates) with a flat and bent form factors are now successful commercial products (http://www.gsmarena.com/samsung_galaxy_round_g910s-5766.php; http://www.samsung.com/global/galaxy/galaxys6/galaxy-s6-edge/). Going forward, significant innovation is expected to continue in advancing the flexible display science, technology, applications, and manufacturing to create compelling new products.

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