Flexible Flat Panel Display

We all want a laptop display that looks as if it was printed on paper, where texts and images would not wash out in bright light and can be viewed from any angle. Better yet, we want displays that can be conjured from our pockets and unrolled to access information anywhere while wireless internet keeps our roll-up display continuously updated. Some day food packages will display health messages and clothing will have displays sewn into the fabrics. You might think of these exciting prospects and doubt their validity. The truth is flexible displays are not commercialized yet, but they are on the brink of becoming a reality as enabling technologies pave the way. Currently there are four types of flexible display close to commercialization, flexible liquid crystal display, flexible organic light emitting diode, gyricon displays, and electrophoretic displays.

1. Enabling Technologies

Before introducing the different types of flex displays, an overview of the enabling technologies is necessary. These technologies include many components that must be compatible and convergent to enable a truly flexible display. The necessary technologies include robust flexible substrates, conducting transparent conducting oxides and/or conducting polymers, electro-optic materials, inorganic and organic electronics, and packaging technologies. In addition to these technologies, many processes must also be developed and optimized in conjunction with the materials development, such as roll-to-roll manufacturing, and printing.

1.1 Flexible Substrates
The primary flexible substrate candidates are plastics and thin glass. Plastic substrates are inexpensive, roll-to-roll processable and can be laminated to multi-layers, but they also impose limitations with respect to thermal processing and barrier performance. Companies are developing coatings for these substrates as well as new plastic substrates to compensate for these constraints. Thin glass substrates exhibit better thermal stability and have higher visual transparency than plastics, but cannot fully bend and are not compatible with roll to roll processing.\textsuperscript{3}

The use of thin metal substrates is a complementary approach to the glass and plastic displays. Flexible metallic substrates provide excellent barrier properties, thermal and dimensional stability over a broad temperature range. In addition, they offer potential integration with backplane technology for active-matrix displays.

1.2 Encapsulation

Since flexible displays utilize polymer materials, a barrier layer is essential in protecting and enclosing the functional materials and layers from oxygen and water degradation. Since organic materials tend to oxidize and hydrolyze, oxygen and water permeation through a flexible substrate is of particular importance flexible electronics. Although single-layer barrier layers do provide the packaged materials with some protection, it appears that multiple layers are necessary for organic light emitting diode applications for long-term stability.\textsuperscript{2}

1.3 Organic and Inorganic Conducting Layers

Indium tin oxide is the typical conducting layer used in display technology because of its excellent sheet resistance and optical clarity. However, the process temperature required for ITO on glass is incompatible with plastic substrates. Therefore lower-
temperature processes have to be developed for ITO in order for it to be considered for flexible display applications. When ITO is deposited on a polymeric substrate, it can crack under tensile strain and cause catastrophic failure. Conduction polymers are also being considered for flexible display applications. Although their sheet resistance and optical properties are not as attractive as ITO, they do have exceptional mechanical properties and low process temperatures. As ITO and conducting polymer technology compete for the conducting substrate solution, there is a new conducting substrate technology based on nanotechnology. Flexible and transparent electrodes have been formed from carbon nanotube dispersions in the combination with wet coating processes and printing techniques.

1.4 Electro-optic Materials

The various types of electro-optic materials for flexible display fall into three categories – emissive, reflective, and transmissive. For emissive applications, small molecules and polymers are being used for OLED applications. In order to have a truly low power display, a reflection mode of operation will have to be implemented on flexible substrates. Polymer-dispersed liquid crystals, encapsulated electrophoretics, gyricon, and bichromic ball composites all operate in the reflective mode. For electronic book and paper applications, an efficient reflective mode display is crucial to eliminate the power consuming backlight.

1.5 Thin Film Transistor

For many electro-optic materials, such as OLEDs, polymer-dispersed liquid crystals, electrophoretics and Gyricon materials, an active matrix backplane will be required for high resolution. The success of TFTs for plastic substrates to date has been
an enabler for flexible flat panel displays and constitutes a very vital component. Currently, poly and amorphous silicon are the standards for TFTs for flexible displays. However, organic thin film transistors on polymeric substrates are also being considered as a candidate for flexible, light weight and inexpensive switching device. ²

1.6 Roll to Roll Processing

Flexible displays are amendable to a roll-to-roll manufacturing process which would be a revolutionary change from current batch process manufacturing. Roll to roll processing is where materials are processed and rolled back up. If roll-to-roll manufacturing technology matures for display processing, it promises to reduce capital equipment costs, reduce display part costs, significantly increase throughput, and it may potentially eliminate component supply chain issues if all processes are performed with roll-to-roll techniques. ² Although batch processing can still be employed to manufacture flexible flat panel displays, many researchers and technologists believe that roll-to-roll manufacturing will ultimately be implemented. ²

2. Flexible LCD

Flat panel displays generally consist of four layers: a back substrate providing mechanical strength; a plane of switches on the substrate that addresses each pixel; a light-controlling layer; and a front panel that holds the top electrodes, encapsulates the light-control layer and offers support. ¹

In liquid crystal displays, the substrate is usually glass coated with amorphous silicon or organic conductor, in which the pixel-switches (TFTs) are patterned. Trapped between these electronics and the front glass is the liquid crystal material, which acts as a
light-controlling layer. The spacing between the two of glass pieces must be carefully controlled to make light-control layer work.¹

Making this sandwich of materials flexible requires finding a set of technologies that can combine to create a matrix of individually addressable pixels that will flex. Since the rigidity of a device increases with the cube of its thickness, reducing the thickness of the glass substrate is an obvious step to take. One method to accomplish this is to etching the glass after the display is complete. Some researchers also tried to replacing the substrate with a flexible plastic, but producing reliable amorphous silicon electronics on a flexible substrate is very difficult using conventional lithographic patterning techniques. In addition, as the display is flexed to different radiiuses, maintaining a fixed electrode gap is extremely demanding.¹

One flexible LCD very close to commercialization is the cholesteric LCD from Kent Displays Inc. This display utilizes a liquid crystal material originally derived from animal cholesterol, hence the name cholesteric. This LCD will be a full-color screen, 160 mm across the diagonal, which is slightly larger than Pocket PC screens. In addition, each color pixel in the display consists of a red, a blue, and a green cell stacked on top of each other, instead of side by side as in today’s full-color laptop LCDs. As a result, the cholesteric LCD’s resolution is far superior than that of current laptop displays.¹

3. OLED display

Organic light emitting diodes (OLED) display is another promising technology for flexible flat panel displays. Flexible OLEDs are very lightweight and durable. Their use in devices such as cell phones and PDAs can reduce breakage. Potentially, OLEDs can be embedded in fabrics to create “smart” clothing.³
3.1 How OLEDs work

OLEDs, like regular LEDs, operate on the principle of electroluminescence, where injected charge carriers recombine and generate light. All OLEDs have four basic components: substrate, anode, organic layers, and cathode. Flexible substrate materials are usually plastic, thin glass or metal foils. The anode is a transparent layer of metal of low work function which serves to remove electrons when a current flows through the device. The cathode is a metal layer of high work function which injects electrons when a current flows through the device. In between the cathode and the anode are the organic layer(s) where transport and recombination of the electrons and holes occur. Depending on the device, the OLED could have one, two or multiple organic layers. Figure 1 shows the structure of a bilayer device. Finally a top cover glass is used to encapsulate the device.

![Figure 1](image)

**Figure 1.** Bilayer OLED consists of two organic layers: emissive and conducting

3.2 How Active-Matrix OLEDs Work

In order to make displays out of OLEDs, a technology called active-matrix display is utilized (figure 2). Active matrix OLED (AMOLED) display consists of OLED
pixels that have been deposited or integrated onto a TFT array to form a matrix of pixels that illuminate light upon electrical activation. The active-matrix TFT backplane acts as an array of switches that control the amount of current flowing through each OLED pixel. The TFT array continuously controls the current that flows to the pixels, signaling to each pixel how brightly to shine. Typically, this continuous current flow is controlled by at least two TFTs at each pixel, one to start and stop the charging of a storage capacitor and the second to provide a voltage source at the level needed to create a constant current to the pixel.³

![Figure 2. Active matrix OLED configuration](image)

3.3 Manufacturing OLED

The major part of manufacturing OLEDs is applying the organic layers to the substrate. This can be economically done in two ways, organic vapor phase deposition and inkjet printing. Organic vapor phase deposition involves a carrier gas and a low-pressure, hot-walled reactor chamber. The carrier gas transports evaporated organic molecules onto cooled substrates, where they condense into thin films. Using a carrier gas increases the efficiency and reduces the cost of making OLEDs.⁵

With inkjet technology, the organic layers are sprayed onto substrates just like inks are sprayed onto paper during printing. Inkjet printing greatly reduces the cost of OLED manufacturing by enabling roll to roll processing. In addition, it allows OLEDs to be printed onto very large films for large displays like electronic billboards.⁵
3.4 OLED Advantages and Disadvantages

The radically different manufacturing process of OLEDs renders it far superior to traditional flat panel displays. Roll to roll processing of OLEDs will significantly lower mass production cost. Since no backlight is needed in OLED displays, flexibility can be achieved much easier than in LCDs. In addition, OLEDs offer bright colorful images with a wide viewing angle and low power.\textsuperscript{5}

The greatest challenge in flexible OLED display is encapsulation and packaging. To protect the OLED from water and oxygen degradation, OLEDs are conventionally sealed with a glass lid using an ultraviolet-cured epoxy resin (figure 3). Flexible OLED packaging, however, is much more challenging. The standard sandwich construction that works well for glass-based displays is insufficient flexible OLED displays where the ability to conform or flex the display is key. A variety of methods to provide flexible encapsulation is currently being developed.\textsuperscript{3}

![Figure 3. Standard OLED encapsulation vs Encapsulation for flexible OLEDs\textsuperscript{3}](image)

Even when the technological challenges are met, there still is a piece missing from the flexible displays puzzle, the production equipment.\textsuperscript{1} Currently there is no infrastructure to produce plastic displays in any volume. It will be a few years before there are sufficient roll-to-roll lines to produce displays that will significantly increase the
market share. ¹ In addition, OLED’s commercialization is restrained by key patents held by Kodak and other firms. It is expected that OLED display technology become widespread once the patents had expired. ⁵

4. Gyri
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Many researchers have attempted to create displays using a light controlling material that require a cell. For example, Xerox Corp experimented with a material called Gyri
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c on are spherical beads with one black and one white hemisphere. The spheres are only 100um in diameter and make a display that is only 200um thick. In the display, the beads are dispersed in a transparent rubber sheet and suspended in oil, allowing it to rotate in response to an electric field. For a one polarity, the white hemisphere faces the viewing direction. Reversing the field polarity will cause the black sphere to be seen. The orientation of the beads stays the same even after the field is removed, allowing images to be stored. In addition, no backlight is needed to view an image on the rubber sheet. The display consumes energy only when forming an image and even this is at very low power. The Gyri
c on rubber sheet is thin, robust and highly flexible. It can be made in large sheets or cut by designers to fit the application. The optical properties of the Gyri
c on are similar to those of paper, making it attractive for future display applications such as book and newspaper readers. ²

5. Electrophoretic Display

Even thinner than the Gyri
c on are electrophoretic displays created by E-ink of Massachusetts. The electrophoretic material consists of a gel suspension of tiny capsules, each containing positively-charged white particles and negatively-charged black particles as shown in figure 4. ¹ A monolayer of the material is sandwiched between
a substrate and a top glass electrode layer. When an electric field is applied between the
top and bottom electrodes, the particles move within the capsules to reflect or absorb
incident light. Varying the field strength or the addressing time on each pixel can also
provide some control of grey scale.¹

**Figure 4.** E-ink’s electrophoretic display. White particles are positively charged, black ones negative. ²

E-Ink's technology has many advantages for flexible flat panel displays. First, the
location of individual pixels is defined by the addressing electrodes, and the electrode gap
is not critical (unlike in LCD).¹ In addition, electrophoretic display is ideally suited for
flexible display applications due to their thin form factor and inherent flexibility.⁶ It uses
ultra-low power and is easily read under any lighting from all viewing angles. While E
Ink's display materials already enable fully flexible displays, flexible backplane
technology for high-resolution, active matrix displays is in the development stage.⁶

6. **Market**

While prototypes of flexible displays have been available for several years, the
first commercial flexible flat panel display product has just become available in 2004 in
the form of a display in digital cameras by Kodak.⁷ Currently, most interest in flexible
display is from the military, where “smart” clothing for outdoor survival is highly desired.
The public still thinks of flexible flat panel display as “cool” but fictional. While flexible
displays could capture revenues in the growing handheld device market, much will
depend on whether low-cost manufacturing can be achieved. As for large area displays
like computer monitor and electronic billboards, much time and processing improvement will be needed before flexible display can take over. Despite the obstacles, flexible display market is estimated to grow 5-7% over the next 2-5 years and the current market projections range anywhere form $100-500 million by 2010.

7. Conclusion

As the components and manufacturing processes of flexible electronics mature, the concept of flexible flat panel display will eventually become a reality. Flexible displays offer tremendous advantages over conventional flat panel displays, like light weight, durability, low power consumption, portability etc. In particular, OLED displays offer bright sharp images at wide viewing angles and bright light, but are difficult to encapsulate. Gyricon and electrophoretic displays have thin form factors and can be viewed at a great range of angels, but their high resolution displays still require development. LCD displays are already mature, but making the sandwich-structured device flexible is still challenging. Once technical difficulties are overcome and roll to roll processing becomes feasible, flexible flat panel displays will widely commercialize and enter all of our lives.

References

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