Overview of Flexible Display Technology- Why, What and When

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Abstract
The concepts of flexible displays and plastic electronics have become some of the most talked about new product opportunities for direct view flat panel displays in recent years. The potential advantages are frequently cited, but the achievement of commercially viable products will require many significant technological innovations in new materials and manufacturing technology. This paper will provide a very broad overview of the rationale for developing flexible displays, the market drivers, the applicable display technologies, the major hurdles that must be overcome and the required evolution of new manufacturing technologies that are essential for successful commercialization. This is intended to provide the outline and context for the series of presentations on specific aspects in each of these topics that will be delivered and discussed at the Plastic Electronics Special Session of the 2005 IMID conference.

1. Introduction
Flexible displays are an inevitable next generation advancement for highly portable, light weight and rugged direct view imaging devices. However, they are very unlikely to replace glass-based displays in major applications such as monitors and television, since these applications do not require or place sufficient value on the unique attributes that flexible displays, which are based upon organic or metal foil substrate materials, enable. Cost is likely to be the major issue which will limit market penetration of flexible substrate devices into markets and product applications which are and will remain “owned” by glass for the foreseeable future. Significant innovation will be required in materials and manufacturing technology to realize this future. Then once introduced and accepted by customers, cost reduction will become the major emphasis to expand the market into new and displacement applications.

Development efforts in recent years have demonstrated the feasibility of such products and it is anticipated that substantial initial offerings may appear in the market by as early as 2007. In the United States, the early adopter for flexible displays will be the U.S. military. The primary motivation is to outfit every foot soldier with very rugged, light weight display devices for battlefield situational awareness. Here, survivability is far more relevant than cost. This early investment in the U.S. and the developments they have and are enabling will overcome the hurdles necessary to produce prototype products in the next few years. Concurrent investment by companies in Europe, Korea, Japan and Taiwan are also addressing many of these same issues and will drive the effort to produce larger volumes of commercial products in later years.

2. Why Flexible Displays
The rationale for developing flexible displays has been stated innumerable times over the last five to ten years. Portable products can benefit from technology that produces lighter, more rugged and more compact display structures. Obviously, displays built upon flexible organic (plastic) substrates, which are conformable, or could be rolled into a cylinder, or even folded have these attributes.

The potential application space is very large. It includes all the portable device applications that currently exist or have been mentioned as potential new market opportunities. It can also include very large area and unique new applications like addressable fabrics and electronic paper. A listing of the applications that are commonly mentioned is provided in the following chart.

The Application Space

■ automotive	■ home appliances	■ smart labels
■ digital albums	■ mobile telephones	■ curved screens
■ games	■ toys	■ electronic paper
■ industrial	■ e-books	■ fabric displays
■ smart cards	■ HH PC	■ web pads
■ camera	■ PDAs	
■ DVDs	■ dynamic advertising	

However, as will be discussed further, a flexible display is considered to be nice, but not essential in the eyes of the typical consumer. Thus market development will not be possible as long as a substantial price premium is attached to the products. And novelty applications alone are unlikely to drive the investment levels necessary to achieve the required innovations in materials and manufacturing. Thus a view must prevail that all the hurdles can be overcome to manufacture flexible displays with similar performance features and at a price target comparable to manufacturing on rigid or possibly conformal glass substrates.

3. Applicable Display Technologies

Three display technologies are predominately mentioned in the context of flexible displays. These are LCD, OLED and electrophoretic (electronic ink). The first plastic substrate prototype products that were produced were LCDs and these provided the early learning experiences. The following facts became clear.

- Plastic substrates are expensive
- Coating quality can cause major problems
- Processing is difficult without heat
- Stretching and shrinkage are disastrous
- New materials are required
- Cost targets will not easily be met

These factors are not unique to the implementation of fully flexible substrates to LCDs alone, but are to some degree applicable to all the display technologies being considered.

Nevertheless, the developers of OLEDs and electrophoretic displays consider that for various reasons their technologies are more applicable to flexible substrates than LCDs. Consequently, their use with flexible substrates is viewed as a significant competitive advantage and is being pursued aggressively by those development communities.

The following two charts list the advantages that are perceived by and the challenges that are faced by the developers of OLEDs and electrophoretic displays in achieving not only a conformable, but a fully flexible, display device.

Display technology – electrophoretic

- **E.g., E Ink, Gyricon, SiPix, and others…**
  - **Advantages for flex**
    - Lenient barrier requirements
    - Simple manufacturing processes
    - Bistability
    - Can be made in large size
  - **Challenges**
    - Slow speed limits addressable applications
    - Passive matrix often not possible
    - Color

Display technology – OLED

- **Advantages for flex**
  - No cell gap or viewing angle problems
  - Good color
  - Wide variety of manufacturing options
  - Screen printing possible
- **Challenges**
  - Stringent barrier requirements
  - Still-immature manufacturing processes
  - Need for active matrix above ~180 lines
  - Current-driven

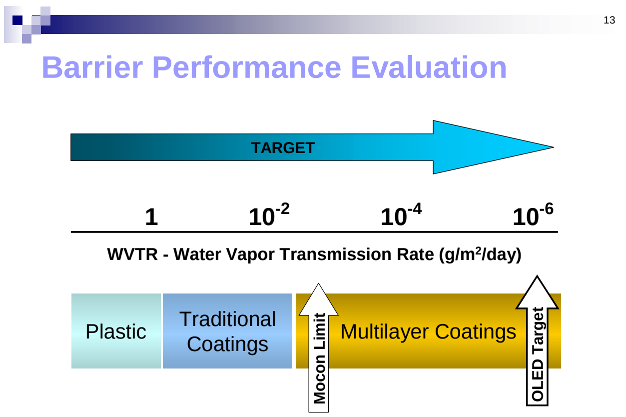
Source – Philips

In this symposium we will hear presentations from companies such as DisplaySearch, E Ink, Philips Research and Universal Display Corp. that will discuss the plans and status to implement these technologies in flexible formats.

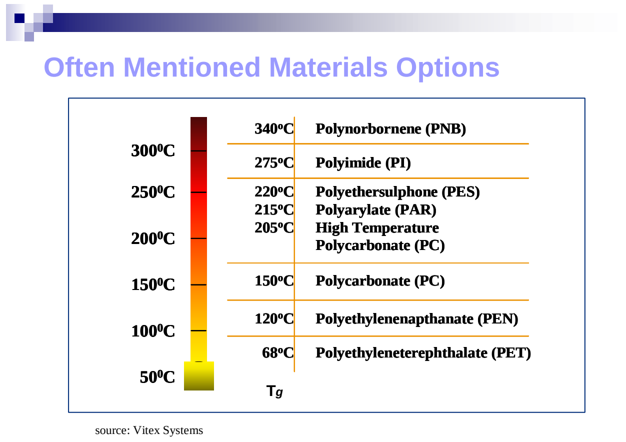
4. Why Don't We Have Flex FPDs Now?

As was mentioned previously, many challenges have been faced in the efforts to bring flexible displays to the market. These challenges reside in developing new materials, manufacturing equipment and process technology, both for the electronic backplanes as well as for the optoelectronic display front planes. This is a consequence of the fact that plastic substrate material properties are very dissimilar to those of display glass. Plastics are far less tolerant of chemicals, high temperatures and mechanical abrasion, and exhibit dimensional instability, environmental sensitivity and rough surface finish, all of which complicate the manufacturing processes and useful service life. Much work has been done, but much remains to be completed.

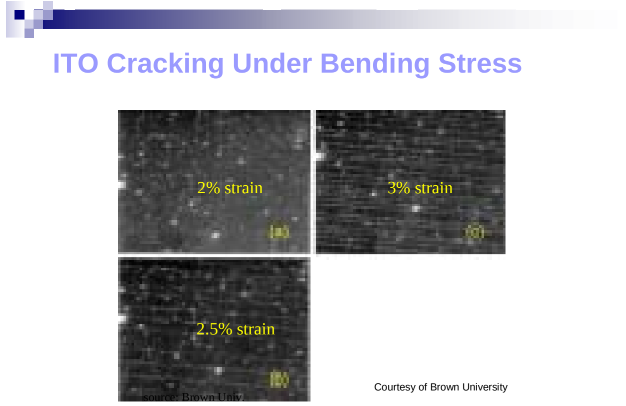
USDC has been engaged in such development efforts for over four years. A heavy emphasis has been placed on innovative materials research to develop barrier layer materials and plastic substrate structures that will have suitable properties, especially with respect to permeation resistance to oxygen and water vapor penetration. This is especially relevant to protecting the sensitive OLED materials which are degraded by such environmental exposure. As shown in the following diagram, many orders of magnitude improvement is required to achieve acceptable values for water vapor transmission rate.



Similar emphasis has been placed on developing improved plastic (polymer) materials by USDC and others, in order to address the need for improved performance for dimensional stability, transparency, surface smoothness and glass transition temperature. The following chart shows the range of values for Tg and that the temperatures are far below glass values.



An alternative to ITO to serve as a transparent conductor will also likely be required if it is desired to roll displays to a relatively small radius of curvature. As shown in the following figure, ITO is subject to extensive cracking when the strain level exceeds 1 to 1.5 %.



Presentations on several of these materials issues will be provided in the symposium by General Electric, Vitex Systems and DuPont Teijin Films.

Although simple passive matrix displays may not face any significant additional materials issues, high resolution displays will require a flexible electronic backplane to switch the pixels, regardless of which display technology is being used. This presents its own unique set of challenges. These will not be reviewed in this overview, but the symposium will have a number of presentations on organic TFTs and other technology options to enable flexible backplanes. Approaches will be presented at this symposium by Hitachi, Seiko Epson, Samsung, PARC and by a number of universities from Korea, Japan and the U.S.

5. Manufacturing Evolution

The manufacturing technology and processes will also change, both because it is necessary (lower temperature; dimensional control; chemical exposure) and because it is desirable to take advantage of lower cost opportunities [solution processing; additive patterning; roll-to-roll in-line (also referred to as "continuous web") manufacturing].

As will be discussed by Paul Wickboldt in his paper, the transition to R-2-R manufacturing will be a huge leap that is unlikely to occur in a single step. Too much is unknown and undeveloped to take the risk of such a commitment. The transition to manufacturing flexible displays will occur in stages from adapted batch processing tools, to islands of automation using R-2-R tools and processes prior to the first step requiring singulation of the individual displays, and eventually (possibly) to a continuous in-line operation. A key point to keep in mind is that the desire to achieve R-2-R manufacturing is driven by the perception that it has the potential to lower manufacturing costs substantially. It will not in and of itself provide any performance improvement in the displays being produced. Thus one must be reasonably confident that the proposed cost targets can be achieved. These are highly dependent on yield levels, web processing speed and equipment utilization levels.

Before the transition to a R-2-R manufacturing line, many new tool developments will be required that adapt current batch tools or develop new tools to take advantage of lower cost manufacturing offered by solution processing. The most commonly cited example is the potential to replace conventional lithography (patterning) with printing options such as ink-jet printing. This has received considerable attention in recent years, especially by those pursuing the PLED technology. Papers offered by Dimatix (formerly Spectra) and Cabot Corp. will provide deeper insights into the status of this approach. Hewlett Packard will describe a potential R-2-R based approach to use imprint lithography as a means to achieve high resolution patterning on substrate materials with low dimensional stability.

6. So, When Will It Happen

Despite the fact that the hurdles are large, they are not any more intimidating than those faced by the LCD industry in its creation, evolution and manufacturing development. Substantial progress has already been seen in materials and new process technologies. Intensive efforts continue as there is a firm belief that a substantial market, that includes both new products and displacement applications, awaits a successful result.

New materials will be the key enabler. They will control how much of the existing, well-defined and well-developed manufacturing process technology can continue to be applied and how many new process technology options must be realized. This will have a tremendous impact on the timing of market introductions.

While manufacturing will almost certainly commence with adaptations of existing batch processing, the drive to transition to R-2-R will remain strong. That is due to the fact that the real gate to market acceptance and penetration is mostly controlled by cost and price. While early market entry and purchase by early adopters can occur at premium prices, substantial volume growth to a meaningful market level will require near price parity with competitive rigid or conformable glass substrate options.

So, when will the production of flexible displays at volume production levels happen? The best estimates (guesses) by industry pundits is no earlier than 2007 and most likely closer to the 2009-2010 time period. But that's not really that far away.