International OLED Technology Roadmap: 2001-2010

J. Norman Bardsley

U. S. Display Consortium

Abstract

Recent advances in the development of organic materials to conduct electricity and emit light should provide the basis for the economic manufacture of active matrix displays built upon organic light emitting diode (OLED) technology, beginning around 2004. The steps leading from laboratory science and prototype demonstrations to high-volume low-cost fabrication in the years 2004-2010 are outlined and the major processing challenges are identified.

Introduction

The flat panel industry has been dominated by liquid crystal displays. LCD technology is advancing so rapidly that it will be difficult for other technologies to compete in the market place, despite all the enthusiasm and innovation that is emerging from research laboratories in both universities and industry. If new approaches such as OLED are to succeed, it is essential that proponents work together to identify and remove the barriers to improved performance and commercialization. It will also be necessary to match the technological developments to the requirements of specific market opportunities. The goal of this roadmap is to facilitate international cooperation in this effort.

Recent advances in the production of light from organic materials have led to intense activity in laboratories across the world and thousands of headlines in newspapers and magazines. Claims have been made of very effective materials, giving almost 100 lumens of light for each Watt of applied electrical energy. However, most early prototype OLEDs have efficacies of less than 1 lumen/Watt. Many have also described the OLED structure as being elegantly simple and have suggested that it may be possible to build OLED fabrication facilities at a small fraction of the cost of AM-LCD plants. However, a high-resolution display is far more complex than a light source. The spatial separation of pixels and the time modulation of the emission may indeed require the fabrication of very complicated structures, in both the mechanical and electronic aspects. OLED plants will also be subject to the same economies of scale that have driven the LCD business to move to ever larger substrates and higher levels of automation.

Since the OLED industry is in its infancy, it is difficult to make precise predictions about its future evolution. Many proposed product introductions have been delayed and early offerings have served to illustrate the difficulties of meeting appropriate fabrication cost targets. Nevertheless, a time schedule will be suggested for discussion by the industry. A more important task is to quantify the technological challenges that must be met if the technology is to result in high-volume manufacturing of high-performance displays. One of the goals in the early stages is to identify alternative ways to meet these challenges. As these issues are understood and the paths to production and commercialization become clearer, greater emphasis will be placed upon specific schedules and more detailed performance parameters.

The foundations for this Roadmap were laid at Workshops in the U. S., Korea and France. It is to be hoped that this progress report will lead to a fourth Workshop, in Japan or Taiwan, to examine and discuss the preliminary findings.

This report will concentrate on the longer term planning needed to develop active matrix OLEDs over the full size range appropriate to direct-view displays and at pixel densities close to the limits of the resolution of the human eye, which is about 300 ppi for viewing distances of 12-15 inches. The planning time scale is 2004-2010.

Matching OLED Characteristics to Potential Markets

The advantages promised by OLED technology include:

- Thin, lightweight, printable displays
- Low voltage, low power, emissive source
- Good daylight visibility through high brightness and contrast
- High resolution (< 5 μm pixel size) and fast switching (1-10 μs)
- Broad color gamut
- Wide viewing angle
- Low bill of materials

Most proponents believe that OLEDs will be able to compete for almost all markets suitable for direct-view displays. Some markets are attractive because they offer the possibility of early entry with relatively simple devices. However, these are not necessarily the markets that are best suited to the technology. In Table 1, the importance of the various attributes of OLEDs for specific applications is ranked either high (H), medium (M) or low.

Table 1: Relative importance of potential OLED display attributes for various applications

	Thin, light	Low power	Clear images	Fast response	Broad color gamut	Wide view	Long life	Plastic substrate
Smart cards	H	H	H	L	L	L	M	H
Head-mounted displays	H	H	H	M	M	M	M	H
Car radios/dashboards	M	L	M	L	L	M	L	M
Voice phones	H	H	M	L	M	L	L	M
Data phones/PDA	H	H	H	L	M	M	L	M
Camera/camcorder viewers	H	H	H	L/M	H	M	L	M
Navigation aids in vehicles	M	M	H	L	M	H	L	M
Portable video phones/games	H	H	H	M	M	M	L	M
Portable DVD players	H	H	H	H	H	M	M	M
Handheld/notebook PCs	H	H	H	M	M	M	M	L
Desktop PCs/workstations	M	M	H	M	M	H	M	L
Transportable TV/DVD	M	M	H	H	H	H	H	L
Dynamic advertising	H	M	H	L	H	H	H	H
Diffuse lighting	H	H	L	L	M	H	H	H

In the lifetime column, an L indicates a nominal lifetime requirement of around 10,000 hours, M denotes about 20,000 hours and H requires over 40,000 hours.

Many obstacles must be overcome before the potential of this technology can be realized. These include:

- Device stability – The performance of the device must not deteriorate markedly with age, either through extended storage or operation. Differential aging between the RGB pixels, or between pixels that are used at different frequencies, must be kept to a few % or less. Exposure to humidity and heat can be particularly damaging. Although encapsulation can reduce the impact of hostile environments, a low cost solution that preserves the advantages of low weight and thin profile has not yet been found.
- Drive scheme - Passive matrix (direct drive) is limited to around 1/4 VGA. To drive devices with more lines requires high voltages, leading to reduced efficiency and additional heat-induced degradation.
- Voltage - The voltage needed to provide adequate current in direct drive pulsed mode is too high for inexpensive CMOS electronics and efficient operation. For active-matrix devices, drift in threshold voltages can lead to loss of control in operation, and so must be minimized or compensated for.
- Current control - The active matrix backplane needed for large area, high-resolution displays must be designed to achieve current control. Multiple TFTs will be needed at each pixel. This increases the cost and requires process development on flexible substrates. The electronics must support relatively large current flows.
- Fine patterns with vivid colors - Although great progress has been made with respect to the active organic materials, better blue, green and red emitters are needed to establish clear superiority over the competing technologies in image quality and efficiency. The production of full-color displays requires further R&D and testing, with respect to the patterning or layering of the luminescent material and electrodes.
- Light extraction – With the present planar structures, most of the light emitted by the organic molecules remains trapped in the diode and does not reach the viewer. An easily-manufacturable structure is needed that directs more light forward without increasing the reflection of ambient light.
- Fabrication costs – No major applications have been identified in which OLEDs will not compete with more mature technologies. Fabrication costs must be reduced to those of competing technologies before significant market shares can be won.

Analyses such as these have led a majority of the OLED community to conclude that the benefits of OLEDs are seriously compromised in passive matrix devices and that active matrix drive is essential for full exploitation of the advantages. However, the development of materials, equipment and manufacturing processes for passive matrix displays is seen as an essential first step in the establishment of an AM-OLED business. The schedule for this development should be coordinated with improvements in the fabrication of the high-performance backplanes that will be needed to drive AM-OLEDs.

Types of OLED Technology - Table 2 summarizes some of the choices that have to be made in designing OLED devices. One of the goals of this roadmap is to provide information for readers that will guide them in making this selection.

Table 2: Major strategic decisions involved in the choice of OLED technology

Small Molecule Materials	**Polymer Materials**
Require vacuum processing More manufacturing experience already gained More mature materials with longer lifetimes Phosphorescent materials are available	Can be deposited at atmospheric pressure More compatible with roll-to-roll processing Lower operating voltages Phosphorescent materials are in early development
Bottom Emitting	**Top Emitting**
Transparent anode technology is mature Pixel electronics reduce aspect ratio	Transparent cathode technology is immature Pixel electronics do not block light emission
Passive Matrix	**Active Matrix**
Simpler electronic array structures High voltage & power needed for high resolution	Challenging TFT array fabrication Lower voltage & power needed for high resolution Potential for smarter displays
Glass Substrate	**Plastic Substrate**
Greater use of traditional LCD processes Glass protects OLED materials Limited benefits of thinness & light weight Fragile if struck or dropped	Low temperature processes needed Plastic is porous to harmful elements Reduced weight & thickness Resistant to dropping and striking Enables conformal displays

Evolution of Performance Parameters

High-Resolution Displays - Three stages are defined in the current Roadmap for high performance displays.

- Stage 1: Proof of principle demonstrations that AM-OLED systems can be designed and fabricated, with performance that is acceptable in some products, but at a cost that is not low enough to capture mainstream markets at high volume.
- Stage 2: Performance reaches the level of competing technologies and manufacturing costs are low enough to support profitable sales for mainstream products
- Stage 3: Cost/performance exceeds that of competing technologies and assures dominance of the technology over a wide range of FPD products

Table 3. Target cost/performance parameters for high-resolution OLED displays

Property	Units	Stage 1	Stage 2	Stage 3
Date	Year	2004	2007	2010
System energy efficiency	%	1	2.5	5
System efficacy	lm/W	4	10	20
Blue saturation	CIE (x+y)	<0.33	<0.25	<0.22
Green saturation	CIE y	>0.6	>0.7	>0.75
Red saturation	CIE x	>0.65	>0.67	>0.7
Lifetime from 300 cd/m^2	hours	10K	20K	40K
Maximum pixel density	ppi	100	200	300
Contrast @ 500 lux	VESA 2.0	50	100	200
Max pixel number		1M	5M	10M
Maximum diagonal size	in	20	40	60
Panel thickness	mm	2.0	1.0	0.5
Maximum voltage swings	V	8	5	3
Panel weight	gm/cm^2	0.5	0.25	0.1
Fabrication costs	$/sq inch	5.00	1.00	0.50

Approximate cost/performance targets for high-performance displays are set out in Table 3. Note that these refer to whole systems with high-resolution pixelation. Values for luminance must allow for the addition of contrast enhancement films and power consumption must include all electrical losses in the panel. Until better correction factors are available, it is estimated that the luminance of the device will be reduced by a factor of 3 from that obtained in the laboratory for planar diodes without contrast enhancement (CE) or pixel formation (e.g. 50% absorption by CE film and 67% aperture ratio). It is also assumed that about one fourth of the power consumption will be consumed by the panel electronics.

Diffuse Lighting Systems - Although the goal of this Roadmap is to chart a course for the development of high-resolution displays based upon OLED technology, there are good reasons to couple this activity with the development of large area OLEDs for use as diffuse light sources. Backlights for liquid crystal displays provide an obvious link at the product level, but there may be more important synergy at the research and manufacturing levels.

When addressing the lighting market, one can focus upon issues of

- conversion efficiency
- device stability and lifetime
- material selection and optimization
- encapsulation
- uniformity over large areas
- manufacturing costs.

Some of the performance characteristics that are critical for full color displays, but not for general lighting are:

- fine patterning
- contrast
- pixel switching
- color saturation.

It seems likely that the demanding cost and weight targets for lighting applications, as shown in Table 4, may be met only by roll-to-roll processing on flexible substrates. The removal of the need to create small pixels and the associated circuitry for switching substantially eases the problems that arise from the poor mechanical and thermal stability of plastic substrates. The problems that arise from porosity remain. Thus the pursuit of the lighting market will provide additional motivation for the development of web processing techniques for OLED fabrication. The importance of reducing the power consumption of lamps installed in homes and business premises is such that additional government funding may be available to stimulate such work. The schedule built into Table 4 is set to accommodate the development of web processing on 1m rolls at high yield. Significant market penetration can be expected soon after 2010, although specialty lighting applications should be viable well before that date.

Table 4. Target cost/performance parameters for OLEDs in diffuse lighting applications

Property	Units	Stage 1	Stage 2	Stage 3	Stage 4
Date	Year	2004	2007	2010	2013
Diode energy efficiency	%	5	12.5	20	30
Diode efficacy	lm/W	20	50	80	120
Color rendering index	CRI	75	80	85	90
Lifetime from 2000 cd/m^2	hours	10K	20K	40K	50K
Maximum panel width	in	14	40	40	>40
Panel thickness	mm	2.0	1.0	0.5	0.5
Panel weight	gm/cm^2	0.5	0.25	0.1	0.1
Fabrication costs	\$/sq m	120	60	40	30

The color rendering index (CRI) is a measure of the quality of illumination for a set of 14 standard color shades.

Materials

Although OLED technology is being developed aggressively by companies that missed the opportunity for early entry into the LCD market, it also offers potential benefits for the major LCD manufacturers. The proportion of fabrication costs for AM-OLEDs represented by the bill of materials has been rising steadily and is now over 50% for some manufacturers. Initial estimates of the costs of the necessary OLED materials are substantially less, but it remains to be seen whether these expectations can be fulfilled. The roadmap goal is to cut these costs in half as shown in Table 5. Note that these figures include all material costs, including the substrates, sealants or dessicants and on-panel electronics.

Table 5. Target costs for total materials and processing for OLED panels in $\$/\text{m}^2$.

Category	Application	2004	2007	2010	2013
Materials	Display cell	500	160	80	-
	Display array	300	160	80	-
	Lighting	80	40	25	20
Processing	Display cell	800	200	100	-
	Display array	1600	440	200	-
	Lighting	20	10	7	4

Organic materials for electroluminescence and charge transport - The Roadmap performance targets for a planar OLED diode in display applications can be taken from Table 3, adjusting for the loss factors cited above

Table 6. Target performance parameters for the basic diode in high-resolution OLED displays

Property	Units	Stage 1	Stage 2	Stage 3
Date	Year	2004	2007	2010
Diode energy efficiency	%	3	7.5	15
Diode efficacy	lm/W	12	30	60
Efficacy-blue	lm/W	3	7.5	15
Blue saturation	CIE (x+y)	<0.33	<0.25	<0.22
Efficacy - green	lm/W	20	50	100
Green saturation	CIE y	>0.6	>0.7	>0.75
Efficacy -red	lm/W	5	12.5	25
Red saturation	CIE x	>0.65	>0.67	>0.7
Lifetime from 1000 cd/m^2	hours	10K	20K	40K
Maximum voltage swings	V	8	5	3

The performance required at each of the three stages will be referred to as level-1, level-2 and level-3. Most of the organic materials that have progressed beyond the laboratory stage can be divided into three classes

- Small molecules with fluorescent emitters
- Small molecules with phosphorescent emitters
- Polymers

The progress that has been achieved to date towards meeting the level-1 performance targets will be reported at the conference, with examples from each class of materials.

Electrodes - Although there have been many efforts to identify an alternative transparent anode material, ITO has most of the desired properties for AM-OLEDs on glass. For plastic substrates that cannot withstand high temperatures, such as PET, the deposition of smooth ITO films with low resistivity (<20 Ω /ð) remains a major challenge. However, the adoption of top-emitting architectures may open up many new possibilities, since transparency is no longer necessary for the anode layer.

The search for the optimal cathode materials is still being actively pursued. Matching work functions to the LUMO (lowest unoccupied molecular orbital) levels of the organics and assuring chemical compatibility are not easy, especially for air-stable materials. In top-emitting structures, the transparency of the cathode should be around 70% or better.

Encapsulation - The present practice of fabricating the OLED on glass and covering with a metal can is regarded only as a short-term expedient. At stage 1, it is assumed that the cover will be a second glass sheet. Improved materials are needed as sealants at the panel edge and as dessicants to absorb water or free oxygen that is left over from fabrication or seeps in through the edges. By stage 2, it is assumed that the second glass sheet will be replaced by a passivating and encapsulating film that is deposited conformally on top of the OLED structures.

When glass substrates are used, either in pairs or with a metal can, the porosity of the edge seal is critical to the device performance. In the absence of getters, the ingress of water and oxygen per day into a small panel must be kept below about

10^{-9} g and 10^{-8} cm^3-atm, respectively. Achieving these levels will perhaps depend more on the adhesion of the sealant to the glass or metal than on the bulk permeability of the sealant material. The incorporation of dessicants is essential to raise the tolerance for this influx as well as to soak up water or oxygen that desorbs from the material inside the device after sealing. More precise data is needed on the requirements for the porosity of seals and the capacity of the dessicant layers.

Substantial progress has been made in the development of multilayer coatings that can compensate for the high porosity of plastic films using alternate layers of inorganic and polymer materials. The rate of ingress that can be tolerated is not exactly known, but current estimates are around 10^{-5} cc/m^2.day.atm for O_2 and 1 μg/m^2 day for H_2O. New measurement techniques have increased our confidence that these target levels can be reached for films that are deposited on flat surfaces. The most immediate challenge is to deposit such barrier layers on top of a finished diode that has been fabricated on glass, and thereby remove the need for a second glass substrate. Planarization of the device structure may be a necessary first step in this process. Eliminating the tapered cathode-patterning structures that are needed for passive matrix devices should simplify this deposition process.

Display Electronics

TFT Arrays – Although many alternatives have been suggested, majority opinion recommends that the low-temperature polysilicon (p-Si) TFT technologies now under development by the LCD industry be adapted for AM-OLEDs. However, much greater control must be provided at the pixel level and several transistors will be needed in each sub-pixel. This is necessary to allow voltage drops across the panel and for variations in the semiconductor materials (e.g. threshold voltage, mobility) as well as in the electrical and optical properties of the pixel diodes. These properties may vary as a result of non-uniformities in fabrication or due to differential aging. The minimum requirement is that the current flowing through each pixel be controlled accurately, through an effective measurement and feedback loop. Monitoring the light emission from each sub-pixel and correcting the current flow would provide an additional level of quality assurance. This could be done after fabrication, using an external test array, or miniature photodetectors could be built into the TFT array in order to provide continuous correction for the effects of differential aging.

Bus lines – The bus lines in OLED displays must carry much higher currents than those in most other FPD panels. In LCDs the bus lines are required only for light control and not for light creation. Although relatively large amounts of electrical power must be delivered to the pixels in PDPs, the use of high voltages means that the current requirements are modest. To reach stage 2 goals with a drive voltage of 5V will require a current density of about 20 A/m^2. This almost certainly cannot be achieved within a sheet of transparent conductor, so that opaque metal lines will be required. Even using copper or an aluminum alloy with low resistivity, the thickness of the bus lines in large panels will be need to be several μm in order to produce an acceptable aperture ratio.

As the panel size increases, achieving rapid switching of pixel intensity also becomes more challenging. The requirements on the capacitance and resistance of conduction lines need to be established more comprehensively, but it is encouraging that prototype displays have been made in the 13-15” size range with 6–8 bit gray scales

Control electronics – The design and manufacture of IC drivers for passive matrix displays remains a matter of concern, especially in regard to cost. One of the advantages of AM-OLEDs is that the drivers can be fabricated on the panel as part of the p-Si TFT array. However it remains to be demonstrated that good yield and performance can be assured, given the added complexity of the OLED circuitry. The external electronics must also be adapted to the new circuits.

Process Development

The overall goal is to develop a suite of processes that is compatible with each of the major OLED types and to obtain a supply of reliable equipment to execute these processes. The generic characteristics are summarized in Table 7.

The strategy underlying the fast track schedule is to match the substrate size used by leading p-Si LCD manufacturers by the year 2007 (The sizes may need to be adjusted to the LCD standards for Gen 6 and Gen 7). It may prove to be difficult to meet this schedule, especially if shadow masks are used for patterning. The cycle time (TACT) must allow for any necessary material handling or set-up time as well as the execution of the particular process step. The target level will also be determined by competition with the LCD industry, rather than performance goals. Acceleration of the schedule for the reduction of the TACT would also be beneficial and should be considered as soon as the process suite is defined. With respect to uniformity, the need to incorporate dopants at low concentrations (0.5 to 2%) provides a special challenge. Although it is tempting to introduce more aggressive uniformity targets in later stages, achieving a constant level as the substrate size increases will be difficult enough. Positional accuracy depends on both metrology and process control and must improve as the desired pixel density is increased. Finally, rapid improvements in yield and system availability are essential for economic competitiveness.

Table 7. Target parameters for AM-OLED processing.

Characteristic	Units	Stage 1	Stage 2	Stage 3
Date	Year	2004	2007	2010
Substrate size (slow track)	mm	400 x 400	730 x 920	1500 x 1800
Substrate size (fast track)	mm	620 x 750	1500 x 1800	2000 x 3000
Roll width (web)	mm	350	1000	2000
Cycle time (TACT)	sec	120	90	60
Uniformity	%	5	5	5
Minimum pixel size	μm	85 x 255	42 x 128	28 x 85
Positional accuracy	μm	5	3	2
Yield - OLED cell	%	70	90	95
Yield – TFT array	%	80	90	95
Total system yield	%	50	80	90
System Availability (uptime)	%	60?	80?	90?

Cleaning and surface preparation – The layers of organic molecules that make up the diode are extremely thin, typically 20-100 nm in thickness. Thus it is imperative that the surfaces onto which these materials are deposited be smooth and clean. Root-mean-square roughness of < 2 nm is often cited, but perhaps a more important requirement is the absence of tall spikes or contaminating particles, particularly containing conducting materials. Finding and eliminating particles of size around 100 nm is very challenging and it may be difficult to prevent the occurrence of localized shorts. Given the high current that would flow across a conducting spike or particle, it may be that such defects will be self-healing, if the material evaporates and can be harmlessly dispersed. The necessary levels of surface cleanliness must be determined, and the adequacy of present cleaning techniques checked, before stage 1 is reached (2004).

The chemical and physical properties of electrode surfaces are also critical. The anode surface may require plasma treatment, after cleaning, to modify the work function or to prevent desorption of oxygen. Before the cathode layer is deposited a thin buffer layer may be required for work function modification or chemical passivation.

Deposition and patterning of active materials – Despite the small thickness of the active layers, deposition times can present a major challenge, especially when using evaporation. Rates of less than 0.5 nm/s are often quoted for some of the active materials. Such rates would imply that multiple chambers would have to be provided for layers of more than 30 μm thickness to meet the 60 s TACT goal. This target should be less of a concern for the deposition of polymer materials by ink-jet or other printing methods. Commercial equipment is already available to print areas of over 1 m^2 per minute at 360 dpi for other applications, and work is underway to adapt these systems to OLED materials. The small layer thickness and the uniformity requirements provide the greatest challenges

The patterning requirements of stage 1 appear to have been met in prototype systems, both for vacuum deposition of small molecules using shadow masks and for ink-jet printing of polymers into predefined pixels. Turning these demonstrations into high-volume manufacturing equipment that meets all targets for size, throughput, yield and uptime is by no means trivial.

TFT array formation – The required performance for individual TFTs can be attained by present techniques on glass substrates and the development of ultra-low temperature processes compatible with plastic substrates is in progress. Maintaining uniformity is the most difficult challenge, especially in the laser annealing steps that are needed to convert a-Si to p-Si. The development of new laser systems might ameliorate these difficulties, but it is almost certain that the electronic circuits will have to be designed to compensate for these variations, as discussed above. The need for multiple TFTs in each pixel may lead to tighter design rules in the fabrication of the array, but these will remain far above the standards of the IC industry.

The companies that manufacture p-Si backplanes for LCDs have not been as aggressive as their a-Si counterparts in reducing the number of mask steps or increasing the substrate size, compared to those that employ a-Si technology. But at least one leading Japanese company has indicated that a 5-mask process is feasible and is planning a 4th generation p-Si line.

It is anticipated that some of the electronics that is off the panel in a-Si LCDs, such as the driver ICs, will be moved into the array. Memory may also be added at the pixel level to facilitate selective refresh or other advances in display control. New architectures for power distribution may also be advantageous.
Bus lines – As discussed above, the thickness of the lines that carry the power across the panel, on both the anode and cathode sides, is likely to exceed 1 μm in large panels. The traditional thin-film techniques of sputtering and etching would require unacceptably long process times and thick-film methods may be preferred. The formation of copper lines by damascene techniques is one possible route. The use of conductive inks, deposited and patterned by printing techniques, is another.

Encapsulation – An optimum strategy to separate the individual panels from others on the substrate, provide protection from environmental damage and to form sturdy electrical connections must be developed. At stage 1, the dominant procedure is likely to be to cover the OLED structures with a second sheet of glass, separate by laser cutting, establish the external electrical connections and then protect the panel edges with UV curable seals. By stage 2, the deposition of a final protective film, using an inorganic/polymer multi-layer coating, should be a viable alternative for high-volume fabrication.

During substrate processing, the conducting lines will often be covered with another layer, especially when an encapsulation film is used. Achieving good electrical contacts with the external circuits may require additional stripping steps that are not needed in making LCDs.

Pilot Fabrication Lines

The experience gained with pilot lines for the manufacture of passive matrix OLED lines has not lived up to the hopes of the more optimistic advocates of the technology. Many product introductions have been delayed and others have not produced displays that can compete with existing technologies in markets that have been highly price-sensitive.

Almost all analysts expect that in AM-OLEDs the organic materials will be deposited on top of the TFT array. This means that the experimentation that is necessary to achieve rapid processing on large substrates with high yields will lead to a lot of very expensive waste material, unless the processes are refined in pilot plants. Therefore, it is essential that further pilot lines be brought into operation during the next few years, for both passive matrix and active matrix panels.

Approximately 30 pilot lines are either in use or will brought up during the next two years. These are mostly designed for glass substrates with dimensions between 300 and 400 mm. Initial targets are for resolution at around 100 ppi and cycle times of 4 minutes, for full color displays. This should provide enough experience to plan high-volume production using both small molecule and polymer materials. Suitable TFT arrays should be available from p-Si TFT manufacturers with a broad selection of substrate sizes on offer (300x400, 320x400, 370x470, 400x500, 550 x 670, 600x720, 620x750, 730x920). The total production of p-Si arrays in 2004 is anticipated to be 2M square meters, which should be adequate to support the AM-OLED pilot lines. A small number of lines for plastic substrates will also be introduced before 2004.

8. Conclusion

If the rate of progress that has been made in the past three years in respect to material properties can be continued for two more years, the foundation for a successful AM-OLED industry should be laid by 2004. In reaching stage 1 of this roadmap, it will also be important to develop and test the complete set of process equipment and to verify the model for scaling up to low-cost high-volume manufacturing at stages 2 and 3.

Given the presence of many groups in this effort, in both industry and academia, and the rapid progress being made by LCD technologies, it is essential that companies be willing to cooperate effectively with others, while defining and protecting their unique intellectual property. The strengthening of industry-wide activities, such as the development of roadmaps and standards, is required, as well as the formation of confidential corporate alliances. Competition needs to be healthy, rather than cut-throat, if the dominance of LCD displays is to be eroded and a profitable OLED industry established.

The road-mapping effort upon which this report is based was coordinated by the U. S. Display Consortium, with assistance from the Electronic Display Industry Association of Korea (EDIRAK) and the European consortium “Flatnet”. An earlier study by academic and industrial researchers was organized by the Optoelectronic Industry and Technology Development Association of Japan. As the focus moves away from basic scientific properties toward manufacturing challenges, it is hoped that these organizations can join with SEMI to produce a complete Roadmap by the year 2004. This consolidated effort should perhaps begin with a Workshop in Japan in late 2002 or early 2003.

Acknowledgments

The author is grateful to colleagues at more than 200 institutions from whom the information in the Roadmap has been gathered. However, until the underlying document is completed and formally reviewed, all responsibility for any inaccuracies or errors in judgment remains with the author. Comments and corrections should be sent to norman@usdc.org.

International
OLED Technology Roadmap:
2001-2010

J. Norman Bardsley
U. S. Display Consortium

norman@usdc.org

OLED: Potential Advantages

- Thin, lightweight, printable displays
- Low voltage, low power, emissive source
- Visibility at all lighting levels
  - high brightness
  - good contrast
- High resolution (< 5 μm pixel size)
- Fast switching (1-10 μs)
- Broad color gamut
- Wide viewing angle
- Low bill of materials

Early Applications of OLEDs: Importance of Display Attributes

	Thin, light	Low power	Clear Image	Fast	Broad color gamut	Wide view	Long life
Smart cards	H	H	H	L	L	L	M
Head-mounted	H	H	H	M	M	M	M
Car radios	M	L	M	L	L	M	L
Voice phones	H	H	M	L	M	L	L
PDA	H	H	H	L	M	M	L
Camera viewers	H	H	H	L/M	H	M	L

H = High; M = Medium; L = Low

Optimal Applications of OLEDs: Importance of Display Attributes

	Thin, light	Low power	Clear image	Fast	Color gamut	Wide view	Long life
Navigation aids	M	M	H	L	M	H	L
Video phones/ handheld games	H	H	H	M	M	M	L
Portable DVD players	H	H	H	H	H	M	M
Handheld/ notebook PCs	H	H	H	M	M	M	M
Desktop PCs/ workstations	M	M	H	M	M	H	M
Transportable TV/DVD	M	M	H	H	H	H	H
Dynamic advertising	H	M	H	L	H	H	H
Diffuse lighting	H	H	L	L	M	H	H

H = High; M = Medium; L = Low

OLED Strategic Decisions

Small Molecule Materials	**Polymer Materials**
Require vacuum processing More manufacturing experience gained More mature materials with longer lifetimes Phosphorescent materials are available	Can be deposited at atmospheric pressure Better for roll-to-roll processing Lower operating voltages Phosphorescent materials not available
Bottom Emitting	**Top Emitting**
Transparent anode technology is mature Pixel electronics reduce aspect ratio	Transparent cathode technology is immature Pixel electronics do not block light emission
Passive Matrix	**Active Matrix**
Simpler electronic array structures High voltage & power needed for high resolution	Challenging TFT array fabrication Low voltage & power needed for high resolution Potential for smarter displays
Glass Substrate	**Plastic Substrate**
Greater use of traditional LCD processes Glass protects OLED materials Limited benefits of thinness & light weight Fragile if struck or dropped	Low temperature processes needed Plastic is porous to harmful elements Reduced weight & thickness Resistant to dropping and striking Enables conformal displays

Roadmap Theme

- Passive matrix OLEDs are of limited interest
  - ≤ 240 lines and 4”??
- Active matrix OLEDs could replace LCDs
  - Lower materials costs
  - Fast response
  - Lower weight and thickness
  - Lower power
- Plastic substrates will follow (3 years later?)
  - Conformable displays
  - Flexible displays

Three Stages of AM-OLED Development

- Stage 1 - 2004
    - Limited volume production
    - Acceptable performance for some products
    - Relatively high manufacturing costs
- Stage 2 - 2007
    - Performance competitive with LCDs
    - Cost competitive with LCDs
- Stage 3 - 2010
    - Performance exceeding that of LCDs
    - Cost lower than LCDs

System Performance Targets

Property	**Units**	**2004**	**2007**	**2010**
Energy efficiency	%	1	2.5	5
Efficacy	lm/W	4	10	20
Blue saturation	CIE (x+y)	<0.33	<0.25	<0.22
Green saturation	CIE y	>0.6	>0.7	>0.75
Red saturation	CIE x	>0.65	>0.67	>0.7
Life from 300 cd/m^2	hours	10K	20K	40K
Pixel density	ppi	100	200	300
Contrast @ 500 lux	VESA	50	100	200
Max pixel number		1M	5M	10M
Diagonal size	in	20	40	60
Panel thickness	mm	2.0	1.0	0.5
Voltage swings	V	8	5	3
Panel weight	gm/cm^2	0.5	0.25	0.1
Fabrication costs	$/sq in	5.00	1.00	0.50

Basic Diode Performance Targets

Property	**Units**	**2004**	**2007**	**2010**
Diode energy efficiency	%	3	7.5	15
Diode efficacy	lm/W	12	30	60
Efficacy-blue	lm/W	3	7.5	15
Blue saturation	CIE (x+y)	<0.33	<0.25	<0.22
Efficacy - green	lm/W	20	50	100
Green saturation	CIE y	>0.6	>0.7	>0.75
Efficacy -red	lm/W	5	12.5	25
Red saturation	CIE x	>0.65	>0.67	>0.7
Lifetime from 1000 cd/m^2	hours	10K	20K	40K
Maximum voltage swings	V	8	5	3

Diffuse Lighting Applications

For lighting applications, one can focus upon

- conversion efficiency
- device stability and lifetime
- material selection and optimization
- encapsulation
- uniformity over large areas
- manufacturing costs.

For lighting applications, one does not need

- fine patterning
- contrast
- pixel switching
- color saturation.

Diffuse Lighting Performance Targets

Property	**Units**	**2004**	**2007**	**2010**	**2013**
Energy efficiency	%	5	12.5	20	30
Efficacy	lm/W	20	50	80	120
Color rendering index	CRI	75	80	85	90
Life from 2000 cd/m^2	hours	10K	20K	40K	50K
Panel width	in	14	40	40	>40
Panel thickness	mm	2.0	1.0	0.5	0.5
Panel weight	gm/cm^2	0.5	0.25	0.1	0.1
Fabrication costs	$/sq m	120	60	40	30

Highlights of Recent Progress

- System performance
- Materials
- Deposition and patterning
- Fabrication plans
- Flexible OLEDs

Progress in System Performance

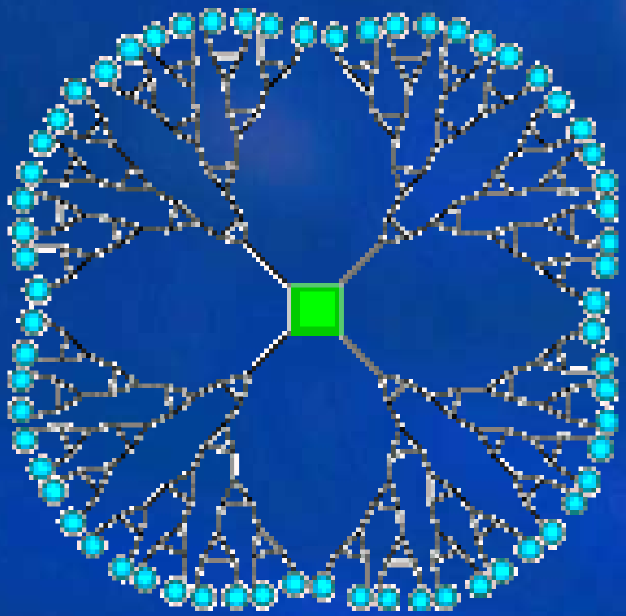
- Large area panels
  - 17” (1280x768) from Toshiba
- Power consumption
  - Sanyo Kodak - 2W for 5.5” display @ 200 cd/m^2
- High contrast at 500 lux
  - 40:1 by Idemitsu Kosan
  - 200:1 by Sony
- Emission through transparent cathode
  - Sony 13” (800x600) panel

Progress in Material Development

- Saturated blue in Sony 13” prototype
  - CIE coords (0.15,0.06)
- Stable blue from Idemitsu Kosan (0.14, 0.17)
  - 10,000 hour half-life from 200 cd/m^2 (eff: 4.7 cd/A)
- Phosphorescent red from UDC/PPG (0.65,0.35)
  - 9 cd/A @ 500 cd/m^2
  - 6000 hour half-life from 500 cd/m^2
- Green dendrimer from Opsys Research Lab
  - Solution-processable small molecule system
  - 51 cd/A @ 100 cd/m^2 and 4.1V

Solution Processable Phosphorescent OLED

Light Emitting Dendrimer



Dendrimers contain

light emitting core (🟩)
dendrons (△)
surface groups (●)

Dendrimer work instigated by Dr Paul Burn, Oxford University & Prof. Ifor Samuel, St Andrews University and exclusively licensed to Opsys.

Source: Damoder Reddy at Opsys

Progress in Deposition and Patterning

- Smooth ITO from Unaxis and others
  - No spikes above 4 nm in height
- Vacuum deposition of small molecules
  - Organic Vapor Phase Deposition from Aixtron
  - Linear evaporation sources from Ulvac and Lesker
  - Shadow masks with 5 µm precision
- Ink-jet printing of polymers
  - 30 mm sub-pixels (70 mm pitch) by Seiko-Epson
  - Custom systems available from Litrex/Spectra

Most current systems are aimed at 350-400 mm substrates

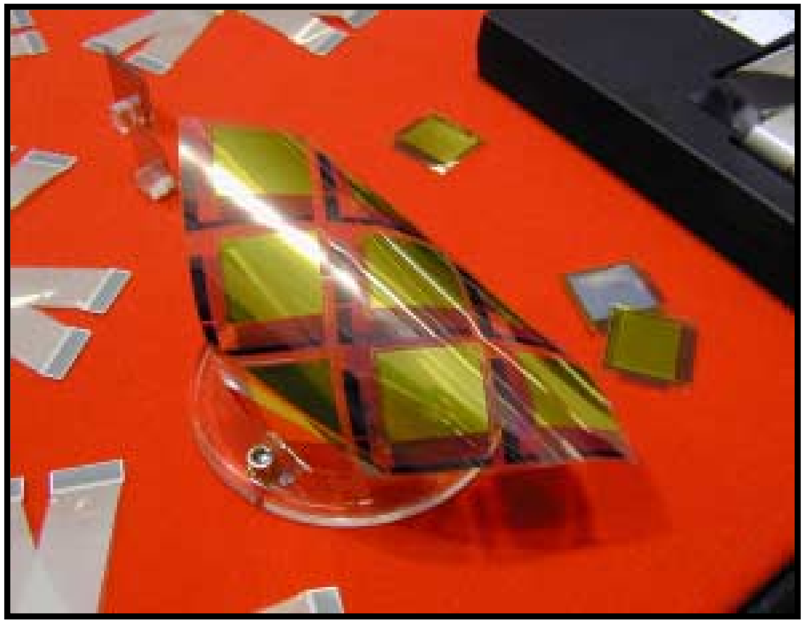
Plans for Fabrication of AM-OLEDs

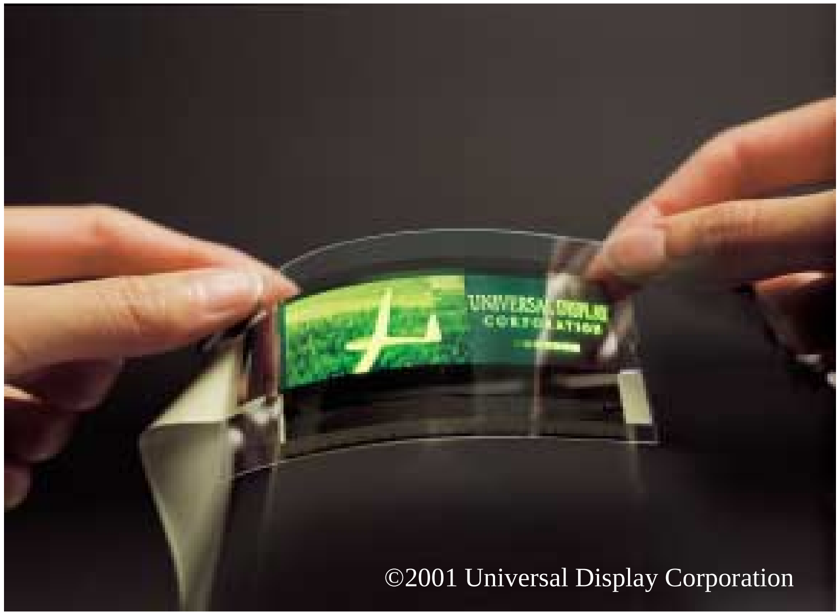
- Small Molecule systems
  - eMagin -Samples of microdisplays (HMD) 2001
  - SK-Samples from 300x400 mm line at Gifu in 2002
  - SK-Production from 550x670 line in Tottori in 2003
  - Pioneer - limited production in 4Q2002
  - Sony - ready for production in 2003
- Polymer systems
  - Toshiba from pilot line in 2Q2002 (Fukaya)
  - DuPont - first products in 2004
- Others
  - SNMD - samples in 2003, commercialization in 2004

Data from company interviews and presentations 2001/2

Flexible OLEDs

- Passive matrix prototypes from
  DuPont and UDC

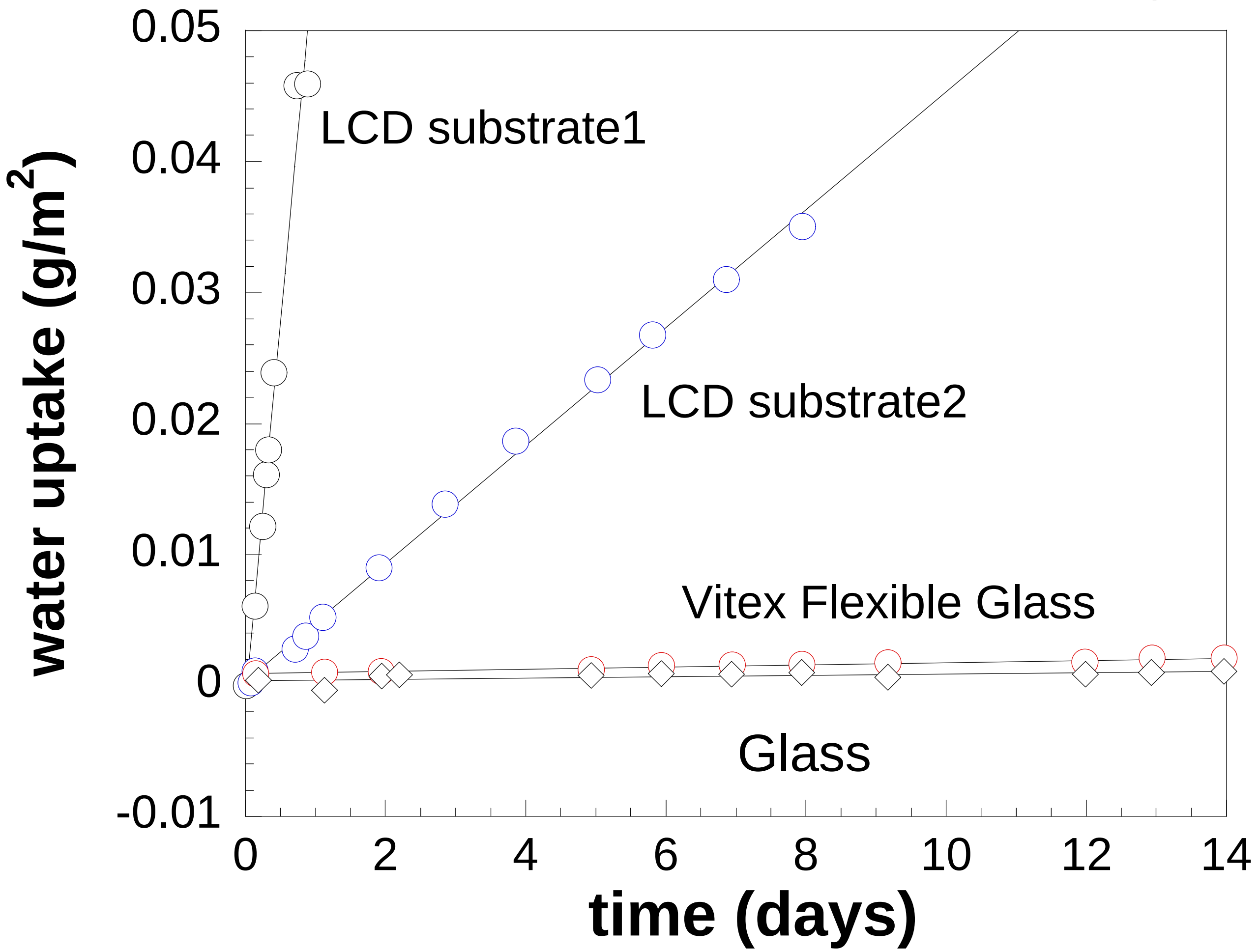




- Progress on coatings for plastic substrates by Vitex

Philips Test of Barrier Films

85° C, 50% RH



Data from Nisato, et. al. IDW 2001

Conclusions

- Material performance is improving rapidly
  - lifetime & efficiency need more work
- Production costs present greatest challenge
  - throughput, substrate area, yield & uptime
  - capital costs for TFT array equipment
  - drive electronics
- Innovation is still needed
  - materials
  - pixel structures
  - fabrication processes
- Long term pathway to new devices
  - thin -> conformable -> flexible