International OLED Technology Roadmap

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Invited Paper

***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 technology, beginning in 2003. The steps leading from laboratory science and prototype demonstrations to high-volume low-cost fabrication in the years 2003 to 2010 are outlined, and the major processing challenges are identified.**

***Index Terms*—Flat-panel displays, manufacturing, organic light emitting diodes (OLEDs), solid-state lighting.**

I. Introduction

THE flat-panel industry has been dominated by liquid crystal displays (LCDs). LCD technology is advancing so rapidly that it will be difficult for other technologies to compete in the marketplace, despite all of the enthusiasm and innovation that is emerging from research laboratories in both universities and industry. If new approaches, such as the organic light emitting diode (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 l/W of applied electrical energy. However, most early prototype OLEDs have efficacies of less than 1 l/W. 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. Further details are contained in a more comprehensive document [1], which covers all major display technologies.

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 in. The planning time scale is 2003 to 2010.

II. Matching OLED Characteristics to Potential Markets

A. Potential Benefits

The advantages promised by OLED technology include:

- thin, lightweight, printable displays;
- low voltage, low power, emissive source;
- good contrast;
- high resolution (<5 μm pixel size) and fast switching (1–10 μs);
- broad color gamut;
- wide viewing angle;
- low bill of materials.

Given the harsh realities of competition in the flat-panel display market, the last advantage may become the critical one.

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 I, the importance of the various attributes of OLEDs for specific applications is ranked either high (H), medium (M), or low (L). In the lifetime column, an L indicates a nominal life-

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TABLE I
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

time requirement of around 10 000 h, M denotes about 20 000 h, and H requires over 40 000 h.

B. Pioneering Products

The first successful attempts to market OLED displays have been by incorporating the panels within systems that are marketed by the same company, such as in the car radios from Pioneer and the shaver from Philips. The experiment by Motorola to incorporate OLED panels as primary displays in mobile phones was soon discontinued and has not yet been repeated. More success seems to have been achieved in the use of simple passive matrix OLEDs in subdisplays, which provide essential data such as the calling number on the outside of clam-shell phones. It is hoped that sales of such panels may reach around 10 M units in 2003. Cost will be critical in this application, since monochrome LCD panels are available for cell phones at around $5 or less.

The first active matrix OLED to reach the market, the 2.2-in full-color panel with 512×218 pixels from Sanyo–Kodak (SK) Displays, was also designed as an electronic viewfinder and review screen for an in-house product, the Kodak LS633 digital still camera. This will provide a critical test, since the vivid color and wide viewing angle of OLEDs are much more valuable in a camera than in a mobile phone, and the low weight and thinness are essential.

The excellent video capability is not exploited in these applications, but will be in portable TVs and DVD players, which should appear within the next few years. The benefits of low material costs would be seen if large-screen OLED TVs could be manufactured in high volume, perhaps in about five years time.

C. Obstacles-to-Market Success

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

Device Stability: The performance of the device must not deteriorate markedly with age, either through extended storage or operation. Differential aging between the red–green–blue (RGB) pixels, or between pixels that are used at different frequencies, must be kept to a few percent 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 180 lines. To drive devices with more lines requires high voltages, leading to reduced efficiency and additional heat-induced degradation. The voltage needed to provide adequate current in direct drive pulsed mode (passive matrix) 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 thin-film transistors (TFTs) will be needed at each pixel. 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 research, development, 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.

D. Choice of OLED Technology

Several strategic decisions must be made in matching OLED technologies to the intended applications. These include the following.

Passive Versus Active Matrix: The fabrication of passive matrix OLEDs is much simpler, since the TFT arrays are not needed. Although the use of passive matrix backplanes does not lead to major deterioration in the quality of the image, as is the case with LCD panels, the power needed to drive passive-matrix displays with high-information contact may be prohibitive. Thus, the majority of the OLED community has concluded 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.

Vacuum Deposition Versus Solution Processing: The organic materials appear to be too fragile to be patterned by standard lithographic techniques, so that any required pixel patterns must be created during the deposition stage. Small molecule materials have been traditionally deposited in vacuum through a shadow mask. However, recent experience by SK Displays suggests that it may be difficult to maintain the desired precision for large high-resolution panels by this technique. The masks are currently to be cleaned every few depositions and replaced after ~ 100 depositions, so that the cost of masks may become a critical concern. The alternative is to mix the active molecules in a solvent to form an ink that can be deposited by printing techniques, such as ink-jet printing. This avoids the use of masks, but the achievement of high resolution so far has been possible only on surfaces that have been previously patterned, with pixel separators or hydrophobic regions. Solution processing has been used traditionally for polymer and dendrimer materials, and research is underway to develop forms of small molecule emitters that can be deposited in this way.

Top Versus Bottom Emission: This distinction refers not to the orientation of the display in use, but as to whether the light is emitted through the substrate on which the panel is manufactured (bottom) or though the lid that is added following fabrication (top). The issue is particularly important for active matrix OLEDs, since the TFT array is manufactured on the first substrate, before the OLED materials are deposited, and the opaque TFTs may block a significant fraction of the transmitted light. However, for all OLEDs, top-emission structures allow one to manufacture on nontransparent substrates and avoid the use of indium–tin–oxide (ITO). Proponents of top-emission devices have argued that light extraction is easier in this configuration. It may be easier to modify the top interfaces by index matching or adding surface structures without complicating the OLED deposition steps. The major obstacle to the development of top-emitting structures has been the availability of transparent cathodes.

Glass Versus Flexible Substrates: One of the deterrents to large-scale investment in OLED fabrication facilities has been the absence of a "killer application." Almost all of the envisaged markets can be also served by LCD panels. It has been argued that the development of flexible displays or very large panels on plastic substrates would give additional advantage to OLEDs because of the very thin structures and suitability for its manufacture using printing techniques. OLED displays on plastic or metal foils could be more rugged than glass-based LCDs, which could be of great value for hand-held devices and military applications. There are two major obstacles to the use of plastic substrates. The first is that they are extremely porous to water and oxygen, both of which lead to rapid deterioration in OLED performance. The second is that inexpensive plastic materials cannot withstand the temperatures at which OLEDs are traditionally processed. Research is underway to develop a set of processing techniques in which the substrate temperature remains below about 100 °C–150 °C. Several polymer substrates are under development that can withstand temperatures up to around 300 °C–350 °C, but, at the moment, these are relatively expensive.

TABLE II
TARGET COST/PERFORMANCE PARAMETERS FOR HIGH-RESOLUTION OLED DISPLAYS

Property	Units	Stage 1	Stage 2	Stage 3
Date	Year	2004	2007	2010
System 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
Life from 300 cd/m^2	hours	10K	20K	40K
Max pixel density	ppi	100	200	300
Contrast @ 500 lux	VESA 2.0	50	100	200
Max pixel number		1M	5M	10M
Max diagonal size	in	20	40	60
Panel thickness	mm	2.0	1.0	0.5
Max 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

III. EVOLUTION OF PERFORMANCE PARAMETERS

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.

A. High-Resolution Displays

Approximate cost/performance targets for high-performance displays are set out in Table II. 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 three from that obtained in the laboratory for planar diodes without contrast enhancement (CE) or pixel formation (e.g., 50% absorption by

TABLE III
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 efficiency	%	5	12.5	20	30
Diode 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
Max 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

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.

It should also be noted that the parameters quoted in Table II provide rough guides and all targets may not be attainable simultaneously.

B. 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 LCDs 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 the issues of

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

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 III, 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 III is set to accommodate the development of web processing on 1m rolls at high yield.

TABLE IV
TARGET COSTS FOR TOTAL MATERIALS AND PROCESSING FOR OLED PANELS IN \$/m^2

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

TABLE V
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 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
Life from 1000 cd/m^2	hours	10K	20K	40K
Max voltage swings	V	8	5	3

Significant market penetration can be expected soon after 2010, although specialty lighting applications should be viable well before that date.

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

IV. DESIRED MATERIAL PROPERTIES

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 IV. Note that these figures include all material costs, including the substrates, sealants or dessicants, and on-panel electronics.

A. Organic Materials for Electroluminescence and Charge Transport

The roadmap performance targets for a planar OLED diode in display applications can be taken from Table V, adjusting for the loss factors cited above.

B. 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 polyethylene teraphthalate (PET), the deposition of smooth ITO films with low resistivity ($<20\ \Omega/\Box$) 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 lowest unoccupied molecular orbital (LUMO) levels of the organics and assuring chemical compatibility is not easy, especially for air-stable materials. In top-emitting structures, the transparency of the cathode should be around 70% or better.

C. 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 small panels must be kept below 10^{-9} g and 10^{-9} 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.

V. Display Electronics

A. TFT Arrays

Although many alternatives have been suggested, traditional opinion holds that the low-temperature polysilicon (p-Si) TFT technologies now under development by the LCD industry may be required for AM-OLEDs. However, much greater control must be provided at the pixel level and several transistors will be needed in each subpixel. 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 nonuniformities 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 subpixel 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 photo-detectors could be built into the TFT array in order to provide continuous correction for the effects of differential aging.

Unfortunately, the fabrication of p-Si TFT arrays requires considerably more steps than that of amorphous silicon (a-Si) arrays. There is a growing belief that it mat be possible to drive AM-OLEDs with a-Si transistors, especially if one uses top-emission structures so that large transistors can be accommodated.

B. 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 5 V may 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 microns 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 in size range with 6–8 bit gray scales

C. 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.

VI. 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 VI.

TABLE VI
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?

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 Generations 6 and 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.

A. 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 a 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.

B. 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/min 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.

C. 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. However, at least one leading Japanese company has indicated that a five-mask process is feasible and is planning a fourth-generation p-Si line.

It is anticipated that some of the electronics that are 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.

D. 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 multilayer 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.

VII. 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 min, 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 (300×400, 320×400, 370×470, 400×500, 550×670, 600×720, 620×750, 730×920). The total production of p-Si arrays in 2004 is anticipated to be two million m^2, which should be adequate to support the AM-OLED pilot lines. A small number of lines for plastic substrates will also be introduced around 2004.

VIII. 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.

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