Global industry status report and roadmap for high performance displays

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ABSTRACT

A summary is provided of a comprehensive industry status report and roadmap available from www.usdc.org. Continued improvements in LCD technology are being driven by home entertainment applications, leading to better color and video response. Competing technologies, such as PDP and OLED and electronic paper must either exploit inherent advantages for such applications or focus on other market niches that are not being addressed well by mainline LCD technology. Flexible displays provide an opportunity for innovative technologies and manufacturing methods, but appear to bring no killer applications.

1. INTRODUCTION

The global flat panel display (FPD) industry is one of the most vital sectors of the electronics industry, growing more rapidly than most other segments. FPD production is currently dominated by active matrix liquid crystal displays (AM-LCD), as shown in Fig. 1. The markets for cathode ray tubes (CRT) and passive matrix LCDs are static and those for plasma display panels (PDP) and Organic Light Emitting Diodes (OLED) are not yet established. The capacity of AMLCD fabrication plants is growing at an annual rate of 40% (Fig.2).

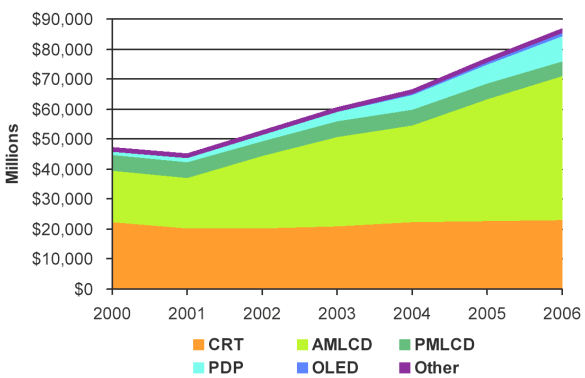
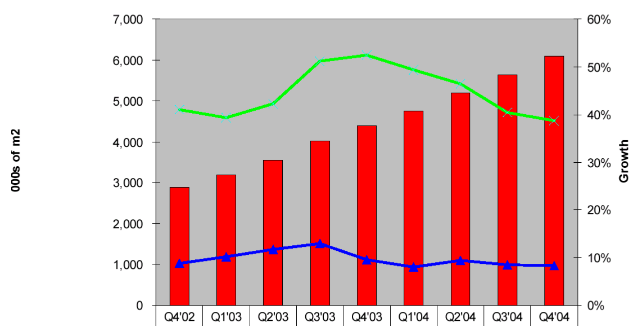


Fig. 1: Predicted growth of display revenues by technology (Source: iSuppli/Stanford Resources)



	Q4'02	Q1'03	Q2'03	Q3'03	Q4'03	Q1'04	Q2'04	Q3'04	Q4'04
AMLCD Capacity	2,885	3,177	3,549	4,012	4,397	4,747	5,195	5,635	6,101
Q/Q Growth	9%	10%	12%	13%	10%	8%	9%	8%	8%
Y/Y Growth	41%	39%	42%	51%	52%	49%	46%	40%	39%

Fig. 2: Growth of capacity for AM-LCD displays (Source: DisplaySearch)

2. ACTIVE MATRIX LIQUID CRYSTAL DISPLAYS

The most expensive element in an AMLCD is the backplane of amorphous silicon (a-Si) thin film transistors (TFTs), that can now be manufactured on glass substrates over 1m square in size. Since the mobility of a-Si TFTs is only 1/1000 that of single crystal Si, it has been argued that the use of better silicon, such as polysilicon (p-Si) or continuous grain silicon (CGS) would lead to higher performance and facilitate the incorporation of added functionality within the pixels of the display. However, manufacturing of p-Si or CGS arrays is much more expensive than that of a-Si, and their use seems to be economic only for small panels. This suggests that the integration of computer systems with the panel may be achieved by placing powerful chips at the edge of the panel (perhaps using chip-on-glass techniques), rather than having extra intelligence embedded in the pixel electronics. Connection technology is the major obstacle to this solution and others still believe that extra functionality should be added at the pixel level. Since the display is now the most expensive and largest component in most personal computer systems, it is likely that other components will be clustered on or around the display, regardless of the manner in which such integration is achieved.

The most important markets for a-Si and p-Si AMLCDs are given in Tables 1 & 2. Computer monitors provide most of the business for a-Si panels, while p-Si panels are most commonly found in hand-held devices. Due to the initial focus upon notebook computer applications and power savings, AMLCDs were initially designed with modest luminance levels and limited viewing angles. As the cost was reduced, significant penetration of the desktop market was achieved, and improvements were made in off-axis viewing, brightness and contrast. Resolution and screen size improved only slowly, with 15" XGA (1024 x 768 pixels) being most popular.

Table 1: Predicted quarterly revenues ($M) for a-Si AMLCD panels (DisplaySearch)

Application	Q3'02	Q4'02	Q1'03	Q2'03	Q3'03	Q4'03	Q1'04	Q2'04	Q3'04
Desktop Monitor	2,447	2,209	2,155	2,366	2,581	3,457	3,424	3,267	3,230
Notebook PC	1,681	1,354	1,147	1,285	1,547	1,723	1,585	1,548	1,520
LCD TV	150	222	225	284	375	465	567	669	748
Mobile Telephone	342	438	399	342	256	277	290	304	306
Industrial	156	150	141	158	165	175	162	165	173
Game	149	140	125	147	171	171	160	156	187
Automobile Monitor	156	134	135	156	148	129	142	161	168
DVD	82	90	94	98	100	96	93	87	82
Camcorder	83	71	72	74	62	56	53	56	53
Mobile Telephone Sub	0	11	35	72	91	115	120	135	141
Others	167	171	143	136	152	132	105	114	122
Q/Q Growth	-9%	-8%	-6%	10%	10%	20%	-1%	-1%	1%
Y/Y Growth	57%	22%	-3%	-14%	4%	36%	43%	30%	19%
Total	5,413	4,990	4,671	5,119	5,648	6,796	6,700	6,663	6,730

Table 2: Predicted quarterly revenues ($M) for p-Si AMLCD panels (DisplaySearch)

Application	Q3'02	Q4'02	Q1'03	Q2'03	Q3'03	Q4'03	Q1'04	Q2'04	Q3'04
Mobile Telephone	61	117	108	190	285	303	405	441	490
PDA	71	90	104	96	125	116	88	103	142
Digital Camera	63	51	44	51	58	50	45	59	72
Industrial	25	33	40	45	53	48	44	50	59
Notebook PC	20	23	25	29	39	46	44	44	43
Camcorder	13	10	11	17	17	18	19	22	22
Digital Album	1	1	2	1	1	1	2	2	2
Q/Q Growth	30%	28%	3%	29%	35%	0%	11%	11%	15%
Y/Y Growth	82%	92%	112%	119%	128%	79%	94%	67%	43%
Total	254	325	334	430	580	582	647	720	830

In wireless devices, such as mobile phones, the pixel count is also restricted because of bandwidth limitations, but technology is available to provide panels with 300 pixels per inch if the market so requires.

The major growth opportunity in the near future is in TV and home theater, with potential annual sales of 150M sets. The competition to replace CRTs for this application is going to be particularly fierce in the large-screen segment, at say 30-70" in diagonal size. The market penetration of LCD and PDP panels in 2002 was still small, as shown in Fig. 3, but is expected to grow rapidly in future years, as shown in Figs. 4-6. Over the short term, LCDs are expected to compete most vigorously in the size range up to about 40", while PDPs will dominate at 42" and above. However the market share of PDPs in the size range of 42-65" will then be challenged by LCDs and by projection systems incorporating microdisplays as light valves. Three forms of microdisplay are contending for this role, the digital micromirror devices (DMD), which are micro-electromechanical systems (MEMS) built on silicon substrates, high-temperature p-Si panels and liquid crystal panels on single-crystal silicon substrates (LCoS). Predictions of the rate at which these technologies will replace CRTs in rear-view projection televisions (RPTVs) are shown in Figs 7 and 8.

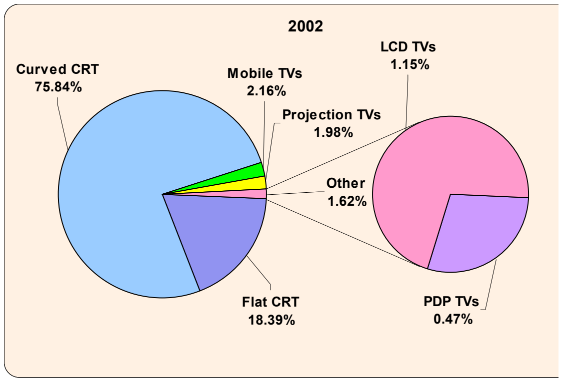


Fig. 3: Television market share by technology in 2002 (DisplaySearch)

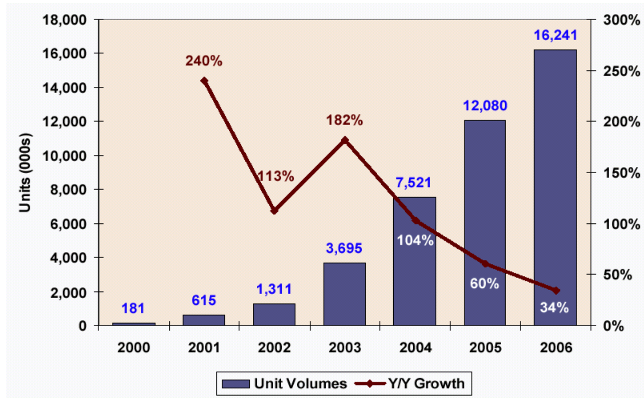


Fig. 4: Anticipated growth in LCD unit sales (DisplaySearch, 2002)

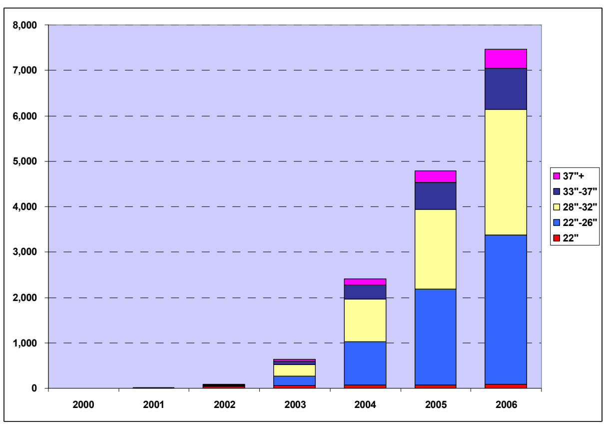
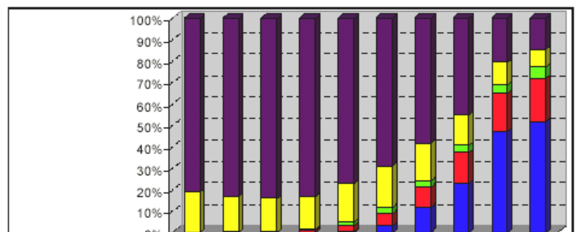


Fig. 5: Projected sales of LCD-TVs by size (DisplaySearch)



	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
Direct View CRTs	81%	83%	84%	83%	77%	69%	58%	45%	21%	15%
CRT Projection	19%	17%	16%	15%	17%	19%	18%	14%	11%	8%
Microdisplay Projection	0%	0%	0%	0%	2%	3%	3%	3%	4%	5%
PDPs	0%	0%	0%	1%	3%	5%	9%	14%	18%	20%
LCDs	0%	0%	0%	0%	0%	3%	12%	23%	47%	52%

Fig. 6: Projected sales of 30"+ TVs (DisplaySearch)

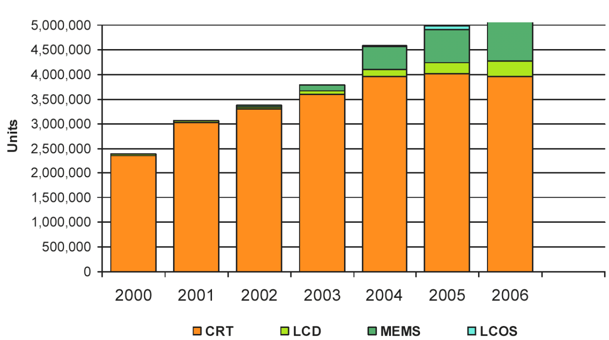


Fig. 7: Projected sales of RPTVs by technology (iSuppli/Stanford Resources)

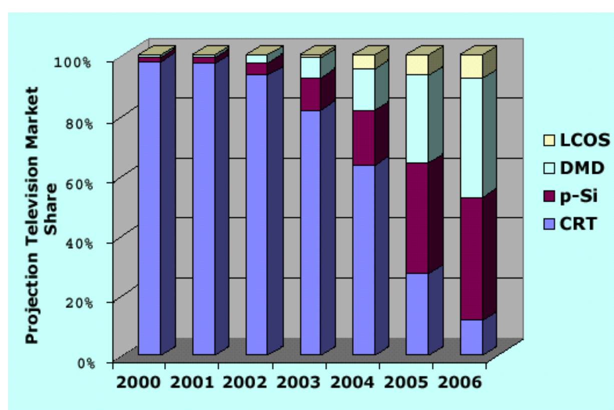


Fig. 8: Projected market shares of RPTVs by technology (McLaughlin Group)

The importance of the TV market to large-volume manufacturers of displays is determining priorities in technology development. The major trends are:

Lower costs: This is being accomplished mainly by increasing the size of the substrate and simplifying process steps. Several 5th generation plants are now in operation, with glass substrates of around 1100 x 1250 mm, and equipment is being delivered for the first 6th generation line (1500 x 1800 mm). As can be seen from Fig. 9, despite the fact that new fabrication lines now cost well over $1B, the share of manufacturing costs associated with depreciation will be relatively low in the next few years. Reducing the costs of display materials and electronics is more critical, providing opportunities for new technologies like OLED and new participants in the supply chain.

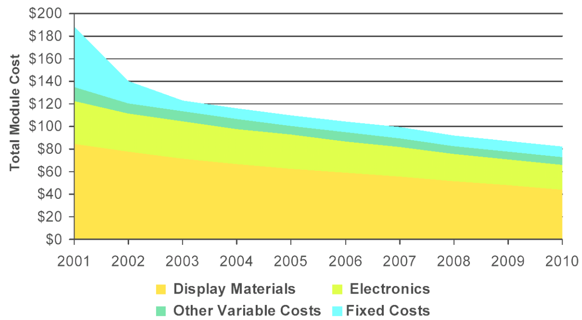


Fig. 9: Anticipated costs of 15" XGA LCD panels (iSuppli/Stanford Resources, 2002)

Panel size: The use of larger substrates enables the production of larger displays. Although it is possible to build panels of 52-54" diagonal on 5th generation lines, only one display is obtained from each substrate and much of the glass is wasted. Fabrication of two panels of 46-48" in size, or six of 25-28", will be more economic. The specifications of the 52" prototype from LG-Philips are shown in Table 3. Similar performance is obtained in the 54" panel from Samsung.

Table 3: Characteristics of prototype 52" LCD-TV from LG-Philips

Specification	52" LCD TV module prototype
Outline Dimension	1228(W) × 743(H) × 56(D)
Viewable Area	52" (Diagonal)
Number of Pixels	1920 × 1080 / 6.2 M sub pixels
Pixel Pitch	0.6 mm / 42 ppi
Number of Colors	16.7 M (RGB 8 bit)
Brightness	500 cd/m^2
Max Contrast Ratio	600:1
Viewing Angle	U/D: 176° R/L: 176° (S-IPS)
Color Saturation	72%
Response Time	12 ms (ODC)
Interface	LVDS
MP Schedule	Q1'04

Faster response: The display of moving images without smearing is not possible with traditional LCD panels. This is partly due to the relatively slow response of the liquid crystals and associated drive schemes, but also due to the address-and-hold nature of the LCD image. The spot scanning mechanism of CRTs is most more suited to the human visual system in the perception of motion. A minimum requirement for LCD-TVs seems to be that the response time is less than the signal integration time of the eye, which is about 15 ms. By using faster liquid crystals, thinner gaps and innovative driving schemes, manufacturers have been able to achieve response times of around 10-12 ms in production. Flashing backlights and other tricks can be used to help the eye-brain system smooth the image. By using alternative LC modes, prototype displays have been built with response times for any gray-scale transition below 5 ms, as shown in Fig. 10.

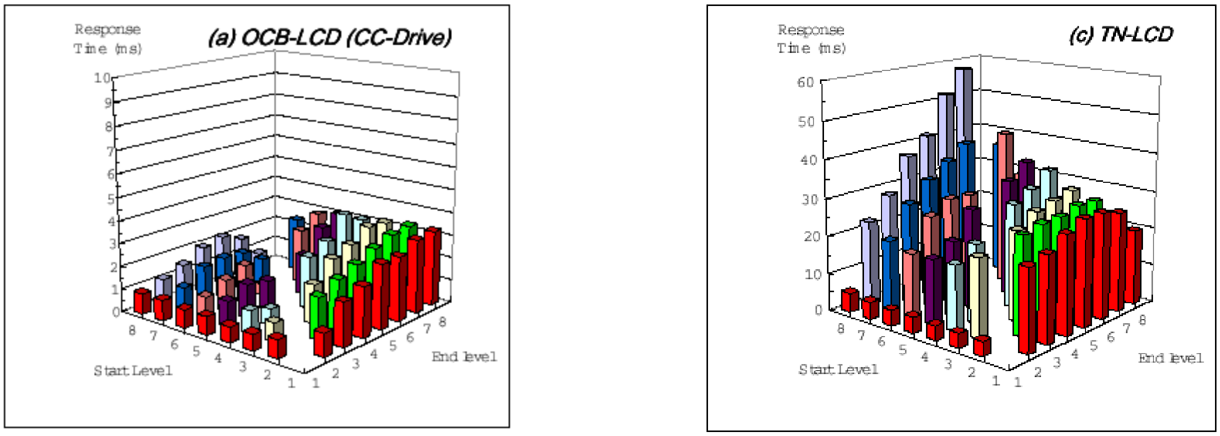


Fig. 10: Response times for inter gray-level transitions for prototype and traditional LCDs (Matsushita, 2002)

Broader color range: The color range of traditional LCDs has traditionally been inferior to that of both CRTs and PDPs. Reducing the bandwidth of color filters leads to greater color saturation, but with a penalty of reduced luminance and contrast. This conflict can be avoided by the replacement of cold-cathode fluorescent (CCFL) backlights by inorganic light emitting diodes (LEDs) with matching color filters, as illustrated in Fig. 11. Color gamuts of up to 120% of NTSC have been obtained by this technique.

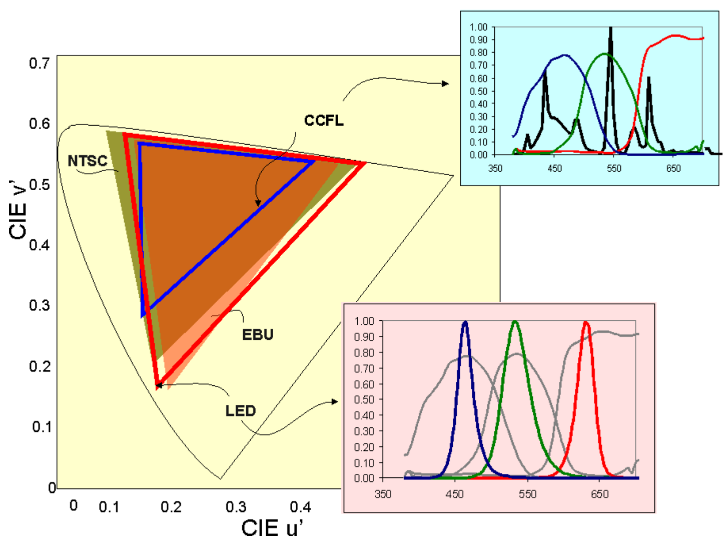


Fig. 11: Color gamut of LCDs with LED and CCFL backlights; the insets show the spectra of light source and color filters (Lumileds)

Higher brightness and contrast: Entertainment applications call for higher peak luminance than is required for personal computer monitors and values of 400-800 cd/m^2 are often claimed. This has been achieved mainly by increasing the power of the backlight system. Relatively little progress has been made in increasing the transmission efficiency of LCD panels, although integration of the color filter and TFT array on a single substrate reduces losses through misalignment. An exciting prospect that is enabled by the reduction in LCD response time is the possibility of eliminating the color filters entirely in favor of frame-sequential color with flashing LED backlights. This should raise the brightness by a factor of 3. Contrast ratios have improved along with the higher brightness levels and are not significantly degraded by ambient light at modest levels.

Better off-axis viewing: The range of viewing angles claimed by LCD-TV manufacturers is almost complete, with up to 176^0 in the horizontal direction. However the criterion used of contrast ratio >10:1 is insufficient to guarantee good images. Other factors like color shifts and gray-scale distortion should also be included in the spec. Nevertheless, the advantage that emissive displays have had over LCDs in off-axis viewing has shrunk significantly.

3. Plasma Display Panels

Plasma panels seem ideally suited for home theater applications, because of their excellent color range, fast plasma response, relatively large pixel size and excellent off-axis viewing. The techniques traditionally used to achieve gray scale control have led to motion anomalies, but these have been ameliorated by recent modifications. The efficacy of the panels in converting power to light has improved and is approaching 2 lm/W. Claims of high values for luminance and contrast have to be interpreted with care, since the peak brightness can only be achieved over a small proportion of the pixels in the screen. Furthermore, the black levels are seriously degraded even at modest levels of ambient light and reflections from the front glass can be annoying when the ambient light is not uniform. These limitations may not be critical for focused viewing of TV or home movies, but reduce the attractiveness of PDPs for computer monitor and signage applications.

The lifetime of PDPs remains a problem and image sticking causes annoyance if the same pattern is displayed continuously over part of the screen. The rapid increase that PDP manufacturers anticipate in consumer sales will depend on the rate at which the cost can be reduced. A major portion of these costs is in the high-voltage electronics, which so far have nor benefited from the miniaturization and increased volumes in the microelectronics industry. A prediction of cost trends is shown in Fig. 12. As shown in Fig. 13, the major growth in the PDP market is expected to come from TV sales.

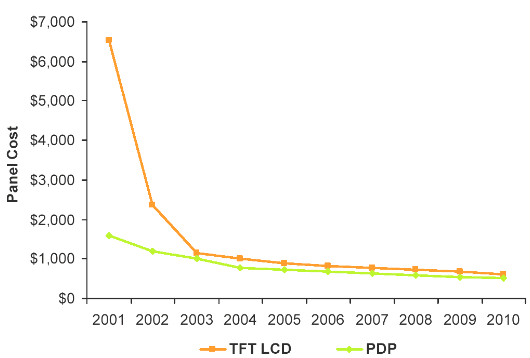


Fig.12: Predicted manufacturing costs for 40" 852 x480 pixel displays
(iSuppli/Stanford Resources)

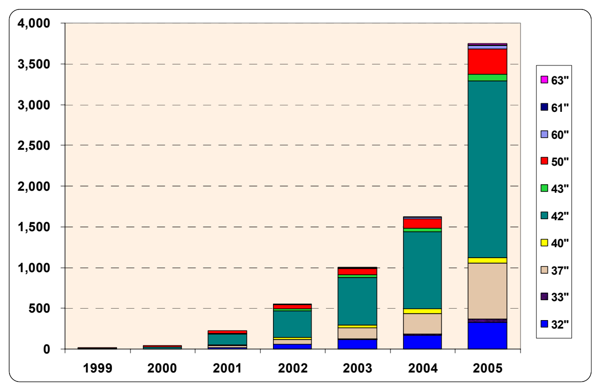


Fig. 13: Projected sales of PDP-TVs by size
(DisplaySearch)

4. Organic Light Emitting Diodes

The progress that is being made in OLED technology is well reviewed in the other papers at this conference. Two important milestones have been reached in OLED manufacturing in recent months, with the production of the first active matrix products by Sanyo-Kodak for Kodak digital cameras and the first large-volume application for passive matrix panels in the sub-displays for mobile phones. Since there are no applications for glass-based OLEDs that are not also addressed by LCDs, the commercial success of OLEDs will depend mainly on the ability of manufacturers to reduce costs so that the premium charged for superior performance is small or negative.

One of the most important potential advantages of OLEDs is that of lower material cost. However, demands for higher performance are leading to added complexity. If polarizers are needed for enhanced contrast in bright environments, color filters are introduced instead of RGB patterning and more complex control electronics is required, the savings in materials costs may be compromised. Almost certainly, initial fabrication will be on smaller lines, with longer process times and lower yields than are obtained using the more mature LCD technology.

The additional fabrication costs for large panels could be substantial if p-Si TFT backplanes are necessary to control the output from each pixel. It has been traditionally assumed that p-Si will be essential, but there is growing evidence that a-Si TFTs may be adequate. Success in panels with a-Si backplanes will also facilitate the use of organic electronics within flexible displays.

4.1 Choice of OLED technology

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

Passive vs. 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 vs 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. In early systems, the masks needed 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 Emission vs. 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 non-transparent substrates and avoid the use of 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 vs 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 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 100-150C. Several polymer substrates are under development that can withstand temperatures up to around 300-350C, but at the moment these are relatively expensive.

4.2 Technology and manufacturing challenges for OLED displays

Three stages are defined in the current roadmap for high performance OLED displays. The approximate dates predicted for the onset of each stage are 2004, 2007 and 2010.

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

In several respects, performance measures must be improved by factors of the order of 2-5. These include:

Photon production efficiency - In OLED devices, light is emitted following the recombination of electrons and holes to form excitons. In systems containing only light atoms, the excitons can be classified as singlet or triplet states and light is only emitted from the singlets. Simple statistical considerations suggest that only 25% of the excitons are formed in singlet states, so that 75% of the energy is wasted. Although it has been argued that the ratio of singlet excitations formed in polymer LEDs may be higher than 50%, the proponents of this view have not yet produced systems with very high efficiency. The clean separation between singlet and triplet states is blurred in heavy atoms, so that in systems containing atoms such as Ir, Pt or La, useful emission may occur from all excitons. Such systems are often called phosphorescent OLEDs, since the emission from the triplet excitons is relatively slow.

Light extraction - The high refractive index of the organic layers and the plastic or glass substrates makes it difficult for light to escape from the OLED structures, unless the direction of initial emission is close to the normal to the substrates. Polymer LEDs appear to have an advantage in this respect in that the long molecules tend to be oriented in the plane of the substrate and the emitted light is stronger in the normal direction. Another critical factor in the determination of the proportion of emitted light that reaches the viewer is the degree of reflection from the electrode opposite the observer. Some designers believe that the best way to increase the contrast of the image in high ambient light is to eliminate reflection from the back electrode. This also avoids interference effects that can lead to color shifts and anomalous angular dependence of the desired image. Others prefer to use constructive interference to maximize the signal in the forward direction or to sharpen the spectral distribution from a subpixel.

Lower voltage - The energy carried by a single visible photon is approximately 2.5 eV. Since it is extremely difficult to produce two photons from a single electron-hole pair, the use of a driving voltage above 3V leads to substantial waste of energy. This is a serious problem for passive matrix OLEDs with more than a hundred lines. Even in AM-OLEDs, minimizing the voltage across the driver ICs as well as the OLED material is necessary to increase the device efficiency.

Viewing angle tunability - Proponents of OLEDs have justly been proud of the quality of the image when viewed off-axis. However, for displays intended for single users, this property comes at a significant price in terms of power consumption. Providing the light that is emitted to towards the edges of the display increases the power consumption. In portable LCDs, the power required to achieve a given on-axis luminance may be reduced by a factor of 5-10 because of the narrow viewing cone. The situation is analogous to the use of a high-gain screen in projection systems. In some applications, such as cell phones, it may be appropriate to sacrifice part of the viwing cone in order to increase battery life.

Lifetimes at high luminance - One of the ways in which some OLED developers overstate the performance of their devices is by stating expected lifetimes at low levels of initial luminance, such as 100 cd/m^2. For display applications (rather than solid-state lighting), the luminance baseline that is used should also correspond to a patterned and switched device with a full complement of optical films and not a single sheet of emissive material. The effects of differential aging need to be considered as well as those a single color. Thus, although progress on lifetimes has been very rapid, further work is needed for many applications.

5. Projection Displays

Once again, many aspects of the technological progress in projection technology are discussed in other papers in this conference An important factor in the commercial market has been the success of Digital Light Processing (DLP) systems incorporating DMD light valves and fully digital electronics, as can be seen from Fig. 14.   One chip systems, using frame sequential color, have been particularly successful in driving down the weight and size of front view projectors.

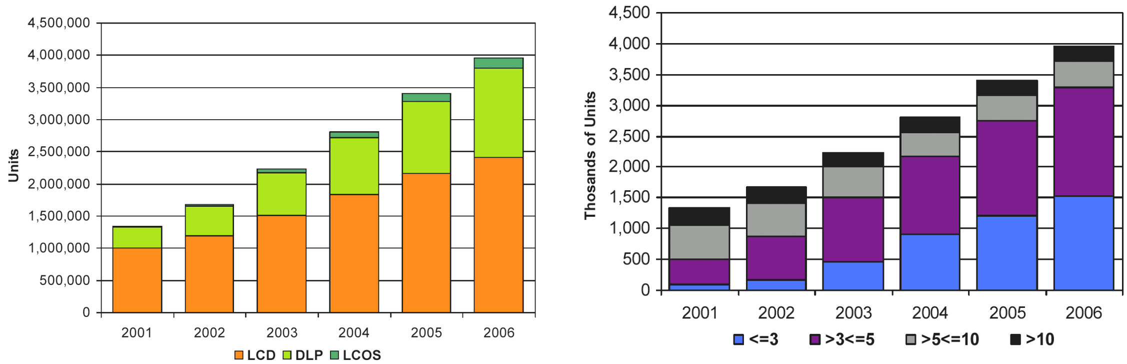


Fig. 14: Anticipated sales of front projectors (a) by technology and (b) by weight in lbs. (iSuppli/Stanford Resources)

6. Reflective Displays and Electronic Paper

Despite the efforts of many groups that have developed alternative technologies, most commercial markets for reflective displays are dominated by traditional LCD panels, partly because auxiliary light sources can be added so that the displays can also be used in dark light. A few years ago, the favored approach was to place a sidelight at the front of the panel, so that the LC could operate in reflective mode when the light was on as well as when it is off. More recently, interest has grown in the use of transflective panels with the auxiliary light at the back. This can be accomplished in two ways. The most popular now seems to be to split each sub-pixel into two regions, one reflective and one transmissive. In some designs, the thickness of the LCD layer and/or color filter in the reflective regime is only half of that in the transmissive area to compensate for the double light path, as illustrated in Fig 14 . The alternative is to include a partially reflective layer, such as a polarization-selective reflector.

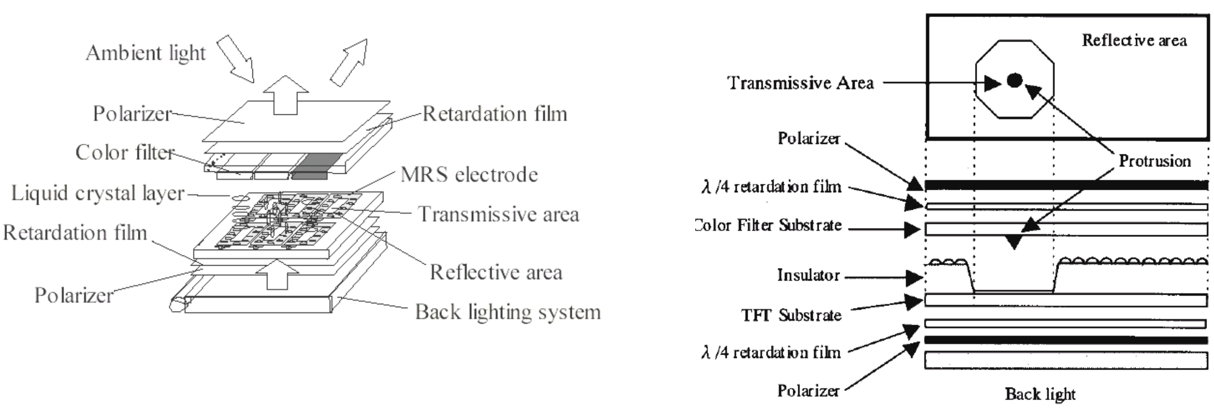


Fig. 15: Transflective displays with multi-zone pixels (a) Sharp (b) Sony

Despite the difficulties in setting up business models for electronic books, magazines and newspapers, several innovative electronic paper displays seem to be close to commercialization. The leading electrophoretic technology, from E-Ink, is described in another paper at this meeting. Gyricon Media hopes to have a viable business by providing wireless schemes to power and update pricing signs in stores, built around their rotating-ball displays. SiPix has an alternative electrophoretic technology that does not appear to require active matrix drive and seems well suited to roll-to-roll processing. Iridigm has a simple scheme to build direct view displays using a MEMS device in which the image is created by optical interference between two reflectors with variable separation. This technology appears to offer a simple route to full color. Several forms of bistable LCDs are under development.

7. Technological Gaps

There are several directions in which the high-volume display manufacturers are not progressing as rapidly as is desired by various special interest groups. These include:

- High information content: Very few displays are available with over 2M pixels. Notable exceptions are the IBM T221 and other products based upon the 9.2M pixel a-Si LCD panel made by International Display Technologies (IDT), and the 3 Mpixel (QXGA) projection systems from JVC, using D-ILA (LCoS) light valves. Commercial interest is increasing in the use of multiple panels, both on desk tops as well as in video walls, and advances have been made in narrowing the bezels of direct view displays as well as matching color and luminance across multiple projectors.
- 3-D: Several major manufacturers have pursued 3-D adaptations of traditional technologies in their research laboratories and at least one product is close to production. Examples of similar technologies, as well as more innovative approaches, are described at this conference.
- Flexible and transparent displays: The only commercial display produced in high quantities on a flexible backplane was an monochromatic PM-LCD panel made by Sharp for hand-held displays. Unfortunately it was introduced at a higher price than that of similar panels on glass a time when monochrome panels were losing popularity. Customers that were willing to pay a premium were faced with the options of obtaining a full-color panel on glass or greater ruggedness through the plastic substrate, and most opted for the former. Although it is clear that the additional ruggedness and lighter weight afforded by plastic displays will be important in some military applications, the development of consumer markets for plastic displays represents a major challenge.

Plans by the Army Research Laboratory to support the development of flexible display technologies are described at this conference. It is hoped that similar programs will soon be initiated to stimulate further work in the other two areas

8. Conclusions

Rapid progress is being achieved by the global flat panel display industry, both in improving performance and reducing manufacturing costs. However, most of these efforts are directed at a relatively small number of products that are of interest to mass markets. Customers who wish to gain a competitive advantage, in either commercial or military contexts, need to work closely with display manufacturers or with intermediary companies that can build high performance systems for critical applications using off-the-shelf components.

Access to the full report on which this review is based can be obtained through the USDC web site at www.usdc.org.