

# OLEDs – Promises, Myths, and TVs

*Much work remains before OLEDs can be considered a player in the display and lighting markets. Among the necessary success factors are mass manufacturing that delivers high yields at competitive costs and a willingness on the part of companies to pursue the technology. But the trends are positive. OLED performance for TVs is outstanding and power consumption is low. Moreover, OLED lighting offers new opportunities in high efficiency, unique form factors, and “relaxing” color temperatures. If the companies practicing the technology follow through with their plans, we should begin to see new competition for TFT-LCDs and LED lighting in the next 3 years.*

by Barry Young

**I**N THE EARLY 1950s, A. Bernanose and co-workers first produced electroluminescence in organic materials. Ching Tang and Steve Van Slyke of Kodak discovered how to produce this light efficiently in the 1980s. But organic light-emitting-diode (OLED) technology came to prominence in the late 1990s when Pioneer delivered its initial product – an area-color display for a car radio – and Nobel Prize winner Dr. Alan Heeger, founder of Uniax, declared OLEDs to be the next great disruptive technology. The availability of a real product and the claims of high contrast ratio, microsecond response time, low power consumption, fully saturated colors, low cost, and thin form factors set up enormous expectations for a technology that appeared to have the potential to displace thin-film-transistor liquid-crystal displays (TFT-LCDs) in virtually every market segment, including small-to-medium and large-area displays and microdisplays. The early delivery of commercial displays set the stage for rapid growth as entrepreneurs in Taiwan and South Korea rapidly joined the field.

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## **The Hype Phase: PMOLED Displays**

Between 1999 and 2005, more than 20 companies in the U.S., Europe, and Asia invested a total of over \$2 billion to build and staff passive-matrix organic light-emitting-diode (PMOLED) fabs in the hopes of replacing LCDs with PMOLEDs. These companies opened and closed faster than a swinging door in their search for the elusive killer application and manufacturing process. Among the areas of focus were mobile phones, MP3s, MP4s, and automobile consoles, as well as the idea of printing on flexible backplanes. In the end, only five companies remained in the OLED business – Pioneer, RiTdisplay, TDK, Univision, and Nihon Seiki, all using vacuum thermal evaporation (VTE) on glass and making primarily monochrome and area-color displays 2 in. or less on the diagonal.

The PMOLED manufacturers were undone by several factors, including a market limited to 2-in. and smaller displays (due to the constraints of passive-matrix multiplexing), rapid price reductions for passive-matrix LCDs (PMLCDs) and active-matrix LCDs (AMLCDs) as competition peaked in 2005, and high voltages caused by the driving method, which restricted battery life in mobile applications. These passive-matrix displays

also brought about a long-term negative marketing effect because the high voltages (>10 V) and high current density ( $J$ ) of low-efficiency early-stage materials led to short lifetimes of ~5000 hours. These lifetimes were not an issue for the types of products that were being fabricated, but created ongoing concerns about OLED lifetimes in general. In fact, such concerns remain to this day, even though lifetimes now exceed 50,000 hours. Revenue for PMOLEDs peaked in Q1 '04 (see Fig. 1) and has been on a downward trend ever since. Manufacturers are selling more displays for less revenue, vitiating the Y/Y positive unit growth.

Display makers soon determined that the market opportunity lay in high-end active-matrix displays, but for these, LTPS backplanes were necessary in order to meet the mobility needs of OLEDs as well as their high-current-density requirements. Early attempts to use a-Si failed. None of the LTPS manufacturers were willing to sell backplanes at a “reasonable” price, so the passive-matrix manufacturers were unable to change their business plans. (For additional discussion of backplane technologies, see “Emerging Technologies for the Commercialization of AMOLED TVs” in this issue.)

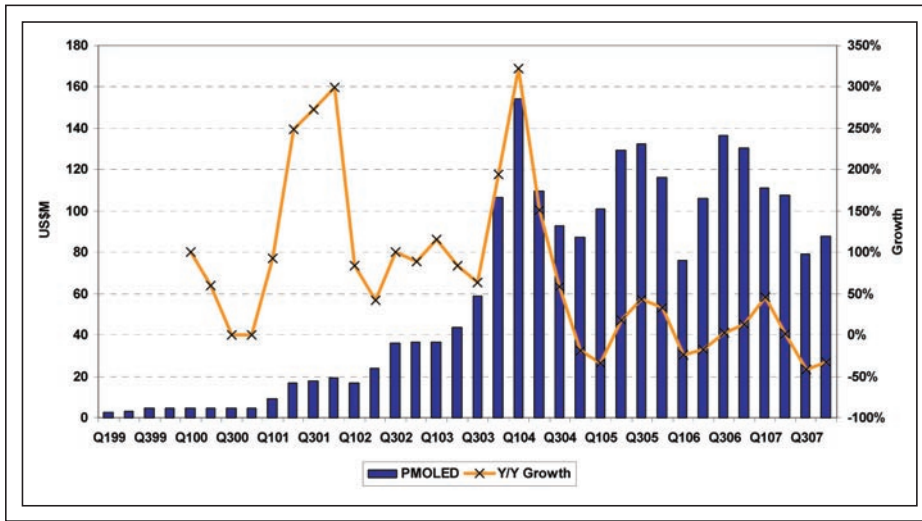


Fig. 1: PMOLED US\$ revenues peaked early in 2004 and have not caught up since. Source: DisplaySearch.

Only TFT-LCD manufacturers had the capital and/or the facilities to make low-temperature polysilicon. But their road was not without constraints. To begin with, the start-up volumes were low due to the use of second-generation fabs. Next, the appeal of higher performance and thin form factors came at a price premium, and new OLED fabs had to compete with fully depreciated TFT-LCD fabs, which increased the cost premium of OLED displays by ~20% compared to that of LCDs.

Kodak recognized this situation early on and developed a multi-phase strategy that included entering into an alliance with Sanyo, one of the leading LTPS suppliers; developing new materials that included device architectures, new deposition tools, and solutions to LTPS yield problems; and creating barriers to entry from other parties by setting the licensing and royalties at unsustainable levels. Sanyo/Kodak gave up in 2005 after failing to achieve its goal of US\$500 million in sales. Sanyo elected to minimize the damage and sell its fabs to Epson, while Kodak retrenched into selling material and licenses.

### Making Headway

These days, AMOLED display makers are on the right track, having resolved the yield issues for LTPS and also having achieved production know-how for full-color displays. Samsung established a new venture to concentrate on AMOLEDs and staffed the new company with senior managers from its LCD and

other groups. Samsung Mobile Display (SMD) is now the industry leader with the only fourth-generation LTPS facility for AMOLEDs and a half-fourth-generation (730 × 460) OLED fab. SMD produces small-to-medium displays for mobile phones, digital cameras, personal media devices, and netbooks up to 5 in. on the diagonal. The production capacity is 1.5 million 2-in. displays per month and that will be extended to 3 million 2-in. displays per month in 2009, and possibly 5 million displays per month in 2010.

Sony, LG Display, and Chi Mei EL (CMEL) also produce AMOLED displays but have a limited capacity of fewer than 100,000 2-in. displays per month. These companies are expected to expand their capacity in 2009 and 2010. TMDisplay, AUO, TPO, and Panasonic will also likely initiate production of AMOLEDs over the next 1–3 years as they sharpen the practice of making high-yield high-performing OLED displays.

### Reality and TVs

The long-term opportunity for AMOLED technology is TVs, where OLEDs shine. Sony, Panasonic, LG Display, and SMD have demonstrated TV prototypes of 25 in. and larger. What has particularly intrigued industry watchers is the potential created with Sony's late 2007 release of the XEL-1, an 11-in. OLED TV that titillates the visual taste buds of both photonics experts and consumers. Virtually without exception, any-

one seeing this TV compared to a TFT-LCD or plasma-display-panel (PDP) TV found that it outperformed these technologies by a wide margin in terms of both image quality and form factor. It has by far the thinnest of form factors in the industry. In addition, OLED TVs appear to have the deepest blacks, the highest contrast ratio, the fastest response time, the widest viewing angles, and the lowest power consumption.

In short, the killer application for OLEDs is the “old” TV. But to compete in the TV market, OLEDs have to continue to progress in the following areas of both technology and manufacturing:

1. **Scaling the backplane.** Building a cost-competitive TV in the sweet spot of the market (32–42-in.) requires a seventh-generation or larger substrate size and starts of 50K units per month to meet the economic size constraints of display manufacturing. LTPS, which currently maxes out at fourth generation, will likely top out at fifth or sixth generation. What is needed is a-Si or a comparable substitute (see “Emerging Technologies for the Commercialization of AMOLED TVs” in this issue.)
2. **Scaling the OLED deposition and patterning process.** The only commercial process available today is VTE through a fine metal mask (FMM). These systems are currently no larger than 730 × 460 (half-fourth-generation) and are also expected to max out at fifth or sixth generation. But new approaches in terms of printing and vertical substrate handling promise to overcome these limitations.
3. **Improving the efficacy and lifetime of the blue material.** The lifetime for material has been ~50K hours to T50 (time to reach 50% of initial luminance). Material makers are demonstrating lifetimes in excess of 100K hours for red and green and greater than 50K hours for blue with an initial luminance of 1000 cd/m<sup>2</sup>. TVs typically operate at 500 cd/m<sup>2</sup>, so there is significant head room. Techniques such as outcoupling and triplet emitters (phosphorescence) are being used to dramatically increase energy efficiency. White-OLED devices and luminaires have already been demonstrated that deliver >100 lm/W, which is competitive with inorganic

# OLED overview

LEDs that have efficacies of >100 lm/W for devices but only approximately half that for luminaires. Unlike inorganic LEDs, the OLED luminaire delivers the same efficacy as the device because for OLEDs the device effectively is the luminaire.

**4. Developing more-efficient material deposition and patterning tools.** The current VTE process with a FMM yields only 3–4% of the material. Most of it remains on the mask because the typical process uses one mask each for red, green, and blue, putting the maximum utilization efficiency at 33%. Today's single-point source also wastes much material because of the distance from the mask. While the low material utilization efficiency is not an issue for small displays, it is a significant cost issue for large ones. Costs for components such as color filters, electronics, and backlights do not scale with size, but organic material does. Several solutions are being developed, including replacing the single source with multiple sources to reduce waste, printing only the exact amount of material required for each subpixel, and eliminating the FMM and using white with a color filter.

**5. Gathering the capital.** Perhaps the most challenging issue for the industry is convincing management that an investment of US\$1–3 billion or more will have a payoff, especially in the current environment of excess capacity and falling prices.

**6. Expanding into other large-area applications.** One of the advantages TFT-LCDs have over PDPs is the wide product range. Although TFT-LCDs enjoy a higher price per square inch for notebooks, monitors, and small-to-medium displays, the price per square meter is significantly less for TV panels in order to compete with PDP displays that operate in only one high-volume market – TVs. The specifications for notebooks and monitors offer significant challenges to OLEDs due to the use of applications such as Word, Excel, the Internet, and e-mail, where 60–70% of the image is white space. This puts the power consumption for OLEDs at a significant disadvantage. TV applications use very little white space and average less than 30% of white across the image.

The forecast for OLED-display revenues is dependant on the number of suppliers that will produce large-area displays and invest in generation six and larger fabs. The small-to-medium market is expected to grow from approximately US\$800 million in 2008 to over US\$4 billion by 2015. But the large-area market is dependent on the actions of SMD, CMEL, Sony, LG Display, Panasonic, and AUO. The following forecast shows the revenue based on up to five of these six companies entering the market. If five do enter the market, the revenue could reach almost US\$14 billion by 2015 (see Fig. 2).

## Reaching Maturity

OLEDs are now reaching maturity and should begin to achieve their early market promise. The keys to growth in OLED market capture are continuous improvement in the following:

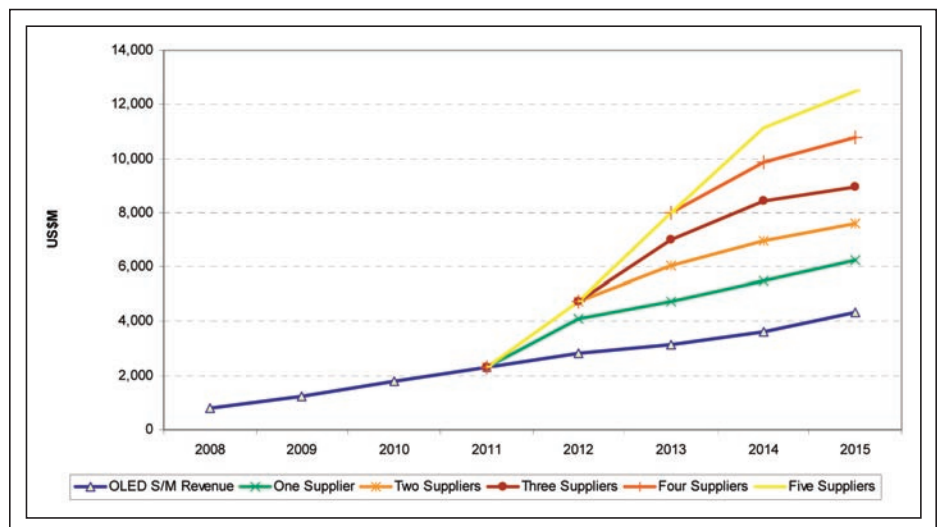
- **Efficiency:** This is currently at 20–30 cd/A and growing to 50–60 cd/A, which will reduce the switching voltage and therefore the power consumption. A typical 3-in. OLED display for a mobile phone uses ~250 mW, but by increasing the efficacy to 50–60 cd/A, the power consumption will decrease to <150 mW, which should compete favorably with the 300–400 mW of TFT-LCDs.
- **Lifetime:** Lifetimes for saturated colors are 250,000 hours for red, 150,000 hours for green, and 50,000 hours for blue. These lifetimes are forecast to grow over

the next 3 years, putting lifetimes at >100,000 hours at 1000 cd/m<sup>2</sup>; significantly exceeding the performance of either LC or PDP displays.

- **Printing:** New approaches to making small-molecule material soluble are expected to lead to slot-printing techniques, which have been demonstrated to be over 70% effective in material utilization, and ink-jet printing may yet prove productive for polymer materials in this new environment.
- **Backplanes:** a-Si is beginning to look more feasible as demonstrated by IGNIS Innovation, which has developed proprietary compensation techniques that adjust for both TFT and OLED performance reductions in real time, and Samsung Mobile Display, which has developed inorganic devices that have sufficient mobility, reliability, and uniformity to support OLEDs.

## Other Uses for OLEDs

Perhaps the kicker in the future will be the use of flexible substrates, which will allow new display formats that can be curved or even rolled, creating new uses for displays. It is likely that lighting, not displays, will be the first application for flexible OLEDs because the backplane requirements are significantly less stringent. OLEDs may soon enter the fast-growing solid-state-lighting market, with complementary tools and device architectures



**Fig. 2:** OLED revenue forecasts increase steeply as additional companies enter the market. Source: OLED Association.

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such as roll-to-roll manufacturing with flexible substrates as demonstrated by GE, low-temperature white panels from Philips and OSRAM, and new outcoupling techniques that double the useable light.

OLEDs are expected to join inorganic LEDs as replacements for incandescent, fluorescent, and high-brightness lighting applications. LEDs have a significant lead in terms of maturity and are strong producers of spot lighting, but can be configured for area lighting. OLEDs are excellent area-lighting replacements for fluorescent lighting because they are more efficient than fluorescent bulbs, last longer, and contain no toxic material, *i.e.*, mercury.

There have been some announcements of organic solar-energy usage to compete with silicon and thin-film photovoltaics, but the efficiency is well below existing silicon or thin-film approaches. It appears to be too early to judge whether OLEDs can be competitive in this application.

### **Summary: Learning the Manufacturing Game**

Much work remains before OLEDs can be considered a player in the display and lighting markets, but demonstrated performance in terms of black level, contrast ratio, efficacy, and lifetime is competitive in today's environment and should improve by 2–4 times over

the next 10 years. What remains is for mass manufacturing to deliver high yields at competitive costs and for companies to be willing to pursue the technology.

In reality, OLED displays are not a threat to TFT manufacturers; they are just an extension of thin-film technology. OLEDs replace the liquid crystal in a display but keep the expensive thin-film technology and the electronics. OLEDs are just another level of device architecture growth, the way VA and IPS improved upon TN-LCDs. TFT manufacturers should thus reap the benefits of a range of new technology created by chemists and chemical engineers. ■