OLED TECHNOLOGY ISSUE

Information DISPLAY

SID
SOCIETY FOR INFORMATION DISPLAY

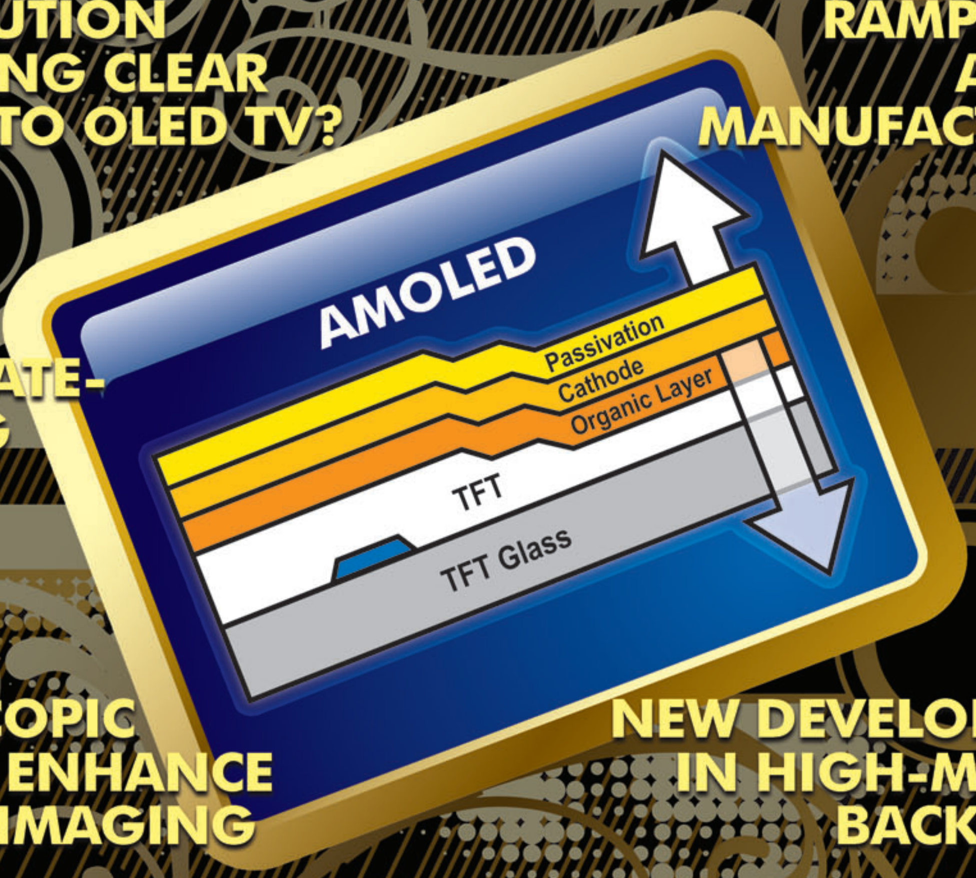
Official Monthly Publication of the Society for Information Display • www.informationdisplay.org

October 2011
Vol. 27, No. 10

OLEDs in Transition

WILL SOLUTION PROCESSING CLEAR THE WAY TO OLED TV?

RAMPING-UP AMOLED MANUFACTURING



SOLID-STATE-LIGHTING UPDATE

STEREOSCOPIC DISPLAYS ENHANCE MEDICAL IMAGING

NEW DEVELOPMENTS IN HIGH-MOBILITY BACKPLANES

Plus

Journal of the SID October Contents

NEWHAVEN DISPLAY
INTERNATIONAL
Specializing in OLED, LCD and VFD Technologies

New
Character and Graphic OLED Displays

- •Eco-Friendly Design
- •Self-Illuminated
- •Faster response times
- •Better contrast ratio
- •Wider viewing angles

NEWHAVEN DISPLAY INTERNATIONAL

Newhaven Display's OLED (Organic Light Emitting Diode) is a brighter, higher contrast display that has faster response times, wider viewing angles and consumes less power than conventional LCD, LED or VFD Displays. OLED displays are self-illuminating so no backlight is required for maximum visibility in all environments. This also allows OLEDs to be significantly thinner than standard VFD, LED or LCD displays. Newhaven Display offers Character and Graphic type OLED displays as complete easy-to-use modules.

For more information visit www.newhavendisplay.com
or contact us at 847-844-8795

ISO 9001:2008 SGS

RoHS
Compliant

SOCIETY FOR INFORMATION DISPLAY

Information DISPLAY

OCTOBER 2011
VOL. 27, NO. 10

contents

2 **Editorial**
Doing More with Less
- *By Stephen P. Atwood*

3 **Industry News**
Solid-State-Lighting Update: OLEDs in Europe
- *By Jenny Donelan*

8 ***Frontline Technology:*** **Clearing the Road to Mass Production of OLED Television**
Advanced material and process developments should help make printed OLED TVs commercially feasible.
- *By David K. Flattery, Curtis R. Fincher, Daniel L. LeCloux, Marie B. O'Regan, and John S. Richard*

14 ***Display Marketplace:*** **OLEDs in Transition**
The OLED industry is in the midst of change – from passive to active matrix and from small to larger sizes. This change is being driven by a significant amount of investment in active-matrix OLED manufacturing facilities – with the ultimate goal being to compete in the TV market. While the industry attempted to commercialize OLED TV in the past, the cost structure and productive capacity were not ready. This time, the pieces are coming together for a successful market entry.
- *By Paul Semenza*

18 ***Making Displays Work for You:*** **Beyond Amorphous-Silicon: New Developments in High-Mobility Backplanes**
New advances in laser-crystallization technology are enabling larger liquid-crystal and OLED displays.
- *By Ulrich Hausmann and David Knowles*

24 ***Frontline Technology:*** **Stereoscopic Display Technologies and Their Applications in Medical Imaging**
The recent evolution of 3-D display technology will impact medical-imaging visualization. 3-D reconstruction systems and stereo cameras are widely available in medical modalities, and improved stereo 3-D visualization will enable new procedures and easier interaction with volumetric anatomy data. New image-quality metrics and basic requirements for stereo 3-D displays are therefore under development.
- *By Luigi Albani, Cédric Marchessoux, and Tom Kimpe*

30 **SID News**
Thomas Peter Brody, SID Fellow and Display Pioneer, Dies at 91.

34 ***Journal of the SID*** **October Contents**

36 **Sustaining Members**

36 **Index to Advertisers**

For Industry News, New Products, Current and Forthcoming Articles,
see www.informationdisplay.org

ON THE COVER: *While the OLED industry attempted to commercialize OLED TV in the past, the cost structure and productive capacity were not ready. Now, the OLED industry is in the midst of a change driven by a significant amount of investment in AMOLED manufacturing facilities with the ultimate goal to compete in the TV market.*

Cover Design: Acapella Studios, Inc.
AMOLED illustration based on artwork provided by Cymer, Inc.

Next Month in *Information Display*

TV Technology Issue

- The TV Landscape for the Near Future
- Why Should I Buy a Plasma TV?
- Hottest Trends for this Holiday Season's TVs
- The Evolution of 3-D Flat Panels: Part II

INFORMATION DISPLAY (ISSN 0362-0972) is published 10 times a year for the Society for Information Display by Palisades Convention Management, 411 Lafayette Street, 2nd Floor, New York, NY 10003; William Klein, President and CEO. EDITORIAL AND BUSINESS OFFICES: Jay Morreale, Editor-in-Chief, Palisades Convention Management, 411 Lafayette Street, 2nd Floor, New York, NY 10003; telephone 212/460-9700. Send manuscripts to the attention of the Editor, *ID*. Director of Sales: Michele Klein, Palisades Convention Management, 411 Lafayette Street, 2nd Floor, New York, NY 10003; 212/460-9700. SID HEADQUARTERS, for correspondence on subscriptions and membership: Society for Information Display, 1475 S. Bascom Ave., Ste. 114, Campbell, CA 95008; telephone 408/879-3901, fax -3833. SUBSCRIPTIONS: Information Display is distributed without charge to those qualified and to SID members as a benefit of membership (annual dues $100.00). Subscriptions to others: U.S. & Canada: $75.00 one year, $7.50 single copy; elsewhere: $100.00 one year, $7.50 single copy. PRINTED by Sheridan Printing Company, Alpha, NJ 08865. Third-class postage paid at Lehigh Valley, PA. PERMISSIONS: Abstracting is permitted with credit to the source. Libraries are permitted to photocopy beyond the limits of the U.S. copyright law for private use of patrons, providing a fee of $2.00 per article is paid to the Copyright Clearance Center, 21 Congress Street, Salem, MA 01970 (reference serial code 0362-0972/11/$1.00 + $0.00). Instructors are permitted to photocopy isolated articles for noncommercial classroom use without fee. This permission does not apply to any special reports or lists published in this magazine. For other copying, reprint or republication permission, write to Society for Information Display, 1475 S. Bascom Ave., Ste. 114, Campbell, CA 95008.

editorial

Doing More with Less

by Stephen Atwood

If you are reading the printed edition of *Information Display*, you probably noticed something different about this October issue. It's printed back to back with the September issue in a new format we are trying. A few months ago, at the urging of the SID Executive Committee, we took a hard look at how we could reduce the production costs of *ID* while still providing the same quality editorial package and reading experience. We don't usually talk about budgets in this space but it may surprise you to know that not only is *Information Display* magazine the official monthly publication of SID, but its production expenses are also heavily subsidized by the Society. Our loyal and very generous advertising partners offset a significant share of the expenses, but for quite a while now it has cost us more to produce *ID* than our advertising activities produce.

The income for SID to operate comes primarily from two sources: membership dues and surplus from the annual Display Week events. From this income, SID pays for all its other activities, including local chapter meetings, the *Journal of the Society for Information Display*, and *Information Display* magazine. Before the economic downturn, the market for print advertising was much better, and we received significantly more income than we do now. We were able to fund our operations at a different level, including travel for freelance reporters, printing and distribution of many more copies of the magazine to people outside of the Society, and much larger editions that included the entire industry directory.

Over the last few years, we have all felt the pinch and SID has not been immune to the challenges of an economy that has been slow to rebound. If you are an SID member, you know what our most recent budgets have looked like and also of the goal to maintain SID's financial health by carefully managing all our activities and expenses. *ID* is not the only part of the Society that is being challenged to do more with less.

I've written recently about how the recession has forced companies to look at new paradigms for doing business and to reset expectations for efficiency metrics such as revenue per employee. Today, there are far fewer people generating much greater work output than just a few short years ago. Unemployment in our industry is still high, partially because companies have discovered that for the time being they can achieve even higher levels of productivity with the same number of employees they have now. I think this is a somewhat unfortunate and hopefully a short-term situation because the amount of stress inherent in the technical workforce today may bring about its own economic backlash someday. Nonetheless, increased efficiency and better productivity are things to be embraced in an ever more competitive global economy. In my office we live the culture of "lean" every day and we constantly challenge ourselves to be a better business because of it.

At *ID*, we have been going through the same cultural transformation, looking at new and more efficient ways to do everything including editorial management, sales, and publications. By necessity, we have reduced our hardcopy circulation significantly while providing on-line access to our entire publication at www.informationdisplay.org. Coming soon, you will see significant improvements in our online presence with the goal of making *ID* more accessible to everyone through multiple electronic formats and services.

(continued on page 32)

Information
DISPLAY

Executive Editor: Stephen P. Atwood
617/306-9729, satwood@azonix.com

Editor-in-Chief: Jay Morreale
212/460-9700, jmorreale@pcm411.com

Managing Editor: Jenny Donelan
603/924-9628, jdonelan@pcm411.com

Administrative Assistant: Ralph Nadell

Ad Coordinator: Michele Klein

Marketing & Sales Dir.: Sharae Johnson

Sales Manager: Christine von Steiger

Solid-State-Lighting Update: OLEDs in Europe

Edison demonstrated his version of the incandescent light bulb in 1879, and light bulbs have roughly resembled that prototype ever since. Even the energy-efficient, squiggly shaped CFL bulbs that have recently begun to replace the familiar pear-shaped ones look like they belong to the same family. As do the stranger-looking, even more expensive, and even longer-lasting LED light bulbs that have started to turn up in stores.

The changing story – and shape – of the light bulb doesn't end here. Although fluorescent and LED light technology permits a range of lighting shapes, OLED lighting promises to change the entire light-bulb paradigm, with lights that are not bulbs at all, but slim, flat, flexible panels – even whole walls of light that can change color and luminosity. OLEDs are also touted for their light quality and environmental friendliness. So far, however, most OLED lighting has not gone beyond a standard 15-cm-sized rigid panel and is not yet mass produced on an affordable scale. So, OLEDs are not going to "take over" right away, but they are definitely coming on, especially in Europe.

That impetus is demonstrated by projects such as the OLED100.eu consortium, which has the overall goal of developing the necessary technologies for efficient OLED applications for the general lighting industry in Europe.[1] The consortium includes lamp manufacturers such as Philips, Novaled, and Osram.

And there is the TOPAS (Thousand Lumen Organic Phosphorescent Devices for Applications in Lighting Systems) 2012 research project, which is "focused on developing innovative material and component architectures as well as new production machines for lighting solutions with highly efficient OLEDs."[2] This project is funded by the German Ministry for Education and Research (BMBF) with OSRAM, BASF, Philips, and Aixtron.

Below is a sampling of what some OLED companies in Europe are doing now with regard to solid-state lighting.

Blue Emitters

Dr. Kai Exner, Senior Manager for OLED Materials at BASF notes: "The focus of BASF's activities is the development of phosphorescent blue emitters. For OLED lighting, red, green, and blue emitters are needed to generate white light. Phosphorescent emitters are necessary to achieve high energy efficiency because they are four times as effective in converting electrical energy into light as fluorescent emitters. Thus far, good red and green emitters are available in the market, but an efficient blue emitter with good color quality and especially long lifetime is the indispensible and still missing piece of the puzzle." This development is being accompanied by work on complementary materials such as hosts and blockers that need to be fine tuned to fit the emitting material.

Fig. 1: The Victory luminaire demonstrates the type of high design concept that OLEDs make possible. Source: Novaled.

Victory Lighting

Novaled in Dresden, Germany, has been a materials and technology provider in the OLED arena for more than a decade. Although the company serves customers in the display and lighting industries (Philips, for example, is a lighting customer), Novaled recently branched out into the luxury luminaire business. Its lighting brand is trademarked Liternity, and the first product to be introduced is the Victory desk lamp, which features four embedded ultra-flat OLEDs in an ultra-strong carbon-fabric base. The Victory lamps, so-called because the two arms form the V for Victory, are coated with several layers of clear lacquer to provide a "3-D" look (Fig. 1). The lamps will become available at selected retailers in the U.S., Europe, and United Arab Emirates this fall at a price yet to be announced.

Novaled's Senior Product Manager, Sven Murano, also addressed some of the current manufacturing challenges. "To make an OLED wallpaper is not primarily just a size problem. Currently, most OLEDs are still being processed on rigid glass substrates and there has not been any product-ready solution with flexible substrates yet. Thus far, only prototypes with limited lifetimes have been shown and one has to expect that no commercial flexible OLED lighting product will appear at least within the next 3–5 years. (For more on the future of OLED manufacturing and flexible backplanes, see the articles "Clearing the Road to Mass Production of OLED Television" and "Beyond Amorphous Silicon: New Developments in High Mobility Backplanes" in this issue.)

"Concerning size," continues Murano, "people are already starting to manufacture on Gen 2 substrates ($\sim 30 \times 40$ cm^2), and tool concepts for significantly larger motherglasses are available." However, at this point the individual panels (that get cut out of the larger motherglass) are somewhere in that standard 15-cm range. This is for two reasons: "The transparent electrodes are not conductive enough to distribute the OLED current evenly over a larger size and the production yield goes down exponentially with size, so the larger you get the better you need to master the process in order to keep the yield up."

New Facility

In August, Osram announced the opening of an OLED pilot-production facility in Regensburg, Germany. The facility, which currently employs 220 people, required an investment of 20 million Euros ($28.9 million). OSRAM says that transparent OLED panels will be manufactured there.

Challenges

The biggest challenge in OLED lighting for companies anywhere in the world, according to Mike Hack, General Manager of OLED Displays for Universal Display Corp., is increased efficiency and lifetime. "We're always pushing for that," he says.

In the January issue of Information Display, *we'll look at OLED and LED solid-state lighting advances in North and South America.*

References

[1] http://oled100.eu/homepage.asp
[2] http://www.oled-info.com/topas-project

– Jenny Donelan

5.5G
OLED Evaporation Solution

GJM Co., Ltd. had succeeded in developing 5.5G evaporation system.

Base on the DSMC simulation, OLED evaporation source of GJM delivers excellent stable deposition rate and uniformity of organic thin film.

A high vacuum chamber has a substrate gripper that help to minimize the deflection of the large glass substrate. And it include the evaporation source shutter and the scanning system that designed as function of molecular behavior of vaporized organic materials.

OLED Evaporation Source

Linear evaporation cell source (BE 550S)	
Type	Large area horizontal evaporation type
Size	5.5G (1300mm x 170mm x 250mm)
Capacity	144hour continuous use
Application	OLED evaporation process (3 ~ 5.5G)
Characteristics	· Evaporation with large area substrate (5.5G) · Stable thin film thickness distribution (<5%) · Evaporator design as function of TS distance · Design and Manufacturing the customized cell source (3 ~ 5.5G)

<BE 550S>

OLED Evaporation Chamber

High vacuum chamber (5×10^{-7} torr) (BE 550C)	
Type	Evaporation processing chamber
Size	5.5G (2000mm x 1600mm x 1100mm)
Application	OLED evaporation test
Characteristics	· Vacuum level: 5×10^{-7} torr · Scanning of a Linear cell source · Holding a large area glass · Include the source shutter

<BE 550C>

See you at IMID 2011, Booth #2018

http://www.gjm.kr, E-mail: shkim@gjm.kr
Tel: +82-41-561-9194, Fax: +82-41-561-9197
#402-1, Dujeong-dong, Seobuk-gu, Cheonan-si, Chungcheongnam-do, 331-957, Korea

CREE HIGH-BRIGHTNESS LEDs

CLX6A

OPTIMIZED FOR OUTDOOR FULL-COLOR VIDEO SIGNAGE, DECORATIVE AND AMUSEMENT APPLICATIONS

Screen Master® Series for matched radiation pattern

Water-resistant package (IPX6-rated)

Small package for high-resolution outdoor video

CLV6A

OPTIMIZED FOR OUTDOOR VIDEO, DECORATIVE AND AMUSEMENT APPLICATIONS

Screen Master® Series for matched radiation pattern

UV inhibitors to minimize effects of long-term exposure

Water-resistant package (IPX5-rated)

CLMVB

OPTIMIZED FOR HIGH - RESOLUTION, INDOOR VIDEO SCREENS AND DECORATIVE APPLICATIONS

Screen Master® Series for matched radiation pattern

Black body for increased contrast ratio

Small package for high-resolution indoor video

C4SMK

OPTIMIZED FOR FULL-COLOR VIDEO, AND OUTDOOR APPLICATIONS

Screen Master® Series for matched radiation pattern

Widest viewing angle available today

CREE HIGH-BRIGHTNESS LEDs ARE CHANGING THE WAY YOU DISPLAY.

REVOLUTIONARY!

Whether indoors or out, Cree High-Brightness LEDs are optimized for your video screen, high-resolution display, channel lighting, decorative and architectural lighting applications. Cree High-Brightness LEDs utilize proven technology to lower your system costs and provide the performance, durability and energy efficiency that you need.

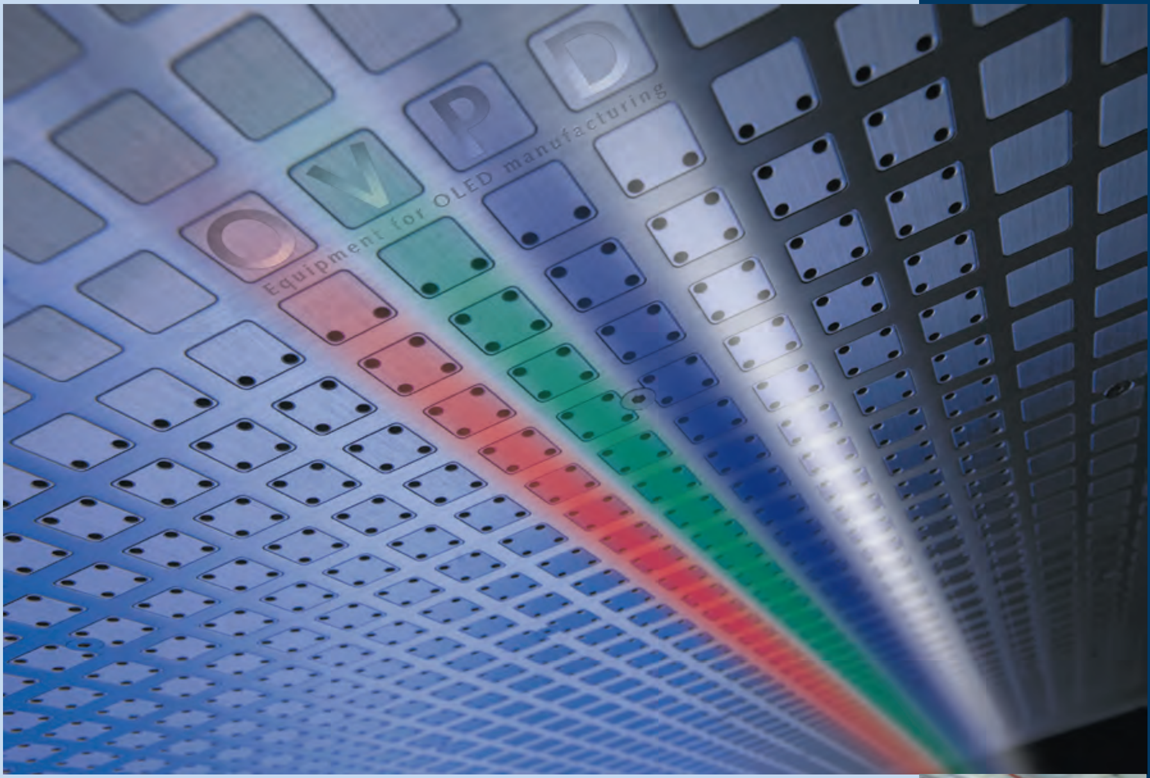
Cree's full line of RGB and white high-brightness LEDs, with through-hole and surface-mount configurations, deliver breakthrough performance at an economical price. It's no wonder we're leading the LED revolution.

Get samples of Cree High-Brightness LEDs or contact an authorized distributor at cree.com/hb or call us at 800-533-2583.

CREE®

AIXTRON

Need solutions for OLED displays and lighting?



OVPD®
Organic Vapor Phase Deposition

AIXTRON supplies low cost and high productivity deposition equipment for organic materials.

AIXTRON delivers scalable, versatile and high performance OVPD® equipment, based on its proprietary Close Coupled Showerhead® technology.

OVPD® technology has been exclusively licensed to AIXTRON from Universal Display Corporation (UDC), Ewing, N.J. USA for equipment manufacture. OVPD® technology is based on an invention by Professor Stephen R. Forrest et al. at Princeton University, USA, which was exclusively licensed to UDC. AIXTRON and UDC have jointly developed and qualified OVPD® pre-production equipment.

AIXTRON

AIXTRON SE · Kaiserstr. 98 · 52134 Herzogenrath, Germany
info@aixtron.com · www.aixtron.com

ALWAYS ONE STEP AHEAD

frontline technology

Clearing the Road to Mass Production of OLED Television

Advanced material and process developments should help make printed OLED TVs commercially feasible.

by David K. Flattery, Curtis R. Fincher, Daniel L. LeCloux, Marie B. O'Regan, and John S. Richard

THE PROMISE of organic light-emitting-diode (OLED) technology has been to deliver displays that are more visually compelling and power efficient than liquid-crystal displays (LCDs) at a lower manufacturing cost. Today, most of this promise has been realized in small-format displays, but manufacturing cost and product price premiums persist. Furthermore, the feasibility of production on glass size comparable to that used for large-format LCDs has yet to be demonstrated.

Three key roadblocks must be removed for the successful mass production of OLED TVs. First, device performance in an actual display produced using manufacturing processes and architectures must achieve competitive thresholds for lifetime, efficiency, and color. Second, the processes and equipment required to accomplish this must be compatible with OLED production on Gen 8 (2.5 × 2.8 m) glass in order to enable competitive capital and fixed-cost productivity. Third, thin-film organic deposition and patterning techniques must significantly reduce the waste of expensive OLED materials. In this article, significant progress toward the removal of these roadblocks through the use of solution processing and particularly nozzle printing of large-format OLED displays will be reviewed.

Material performance in actual devices continues to rapidly improve through both process improvements and new material developments. The latest suite of solution materials achieves performance that now meets the minimum threshold required for commercial OLED television.

Over the last 15 years, dramatic increases in the scale of manufacturing have allowed LCDs to enjoy significant decreases in fixed and capital cost per square meter. Evaporative deposition of OLED material through a fine stencil mask is the generally established process. Unlike fine-metal-mask evaporation techniques, which have fundamental challenges to overcome for achieving production scale, the bulk of the equipment and tooling required for solution-processed OLED devices is commonly available at all scales. The critical exception is the nozzle printer, for which commercial systems have been produced up to full-size Gen 4 (0.7 × 0.9 m). The basic technology is fundamentally scalable, however, with engineering under way to deliver a full-size Gen 8 system.

Historically, 5–10 grams of OLED material are consumed for each gram of material evaporated onto the area of the substrate. Solution processing of coated and printed layers reduces consumption of materials to a fraction of this value. Through material and process developments that enable the solution processing of small-molecule OLED materials, the per-gram cost structure of most of the material layers has been made competitive with materials used for evaporation, which

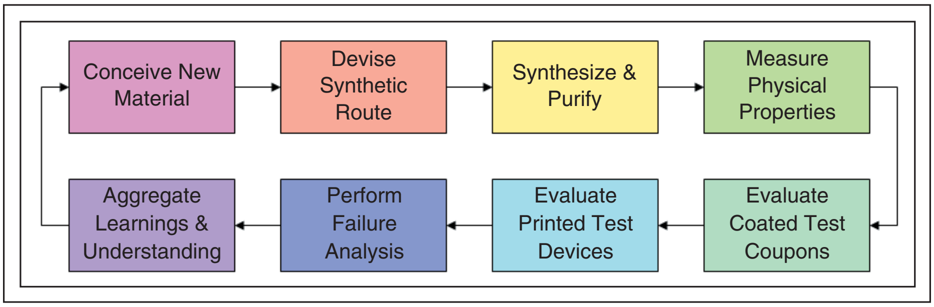


Fig. 1: The integrated material development process contains eight steps.

David Flattery *is the Operations Business Leader for DuPont Displays.* ***John Richard*** *is the Business Manager for DuPont Displays.* ***Curtis Fincher****,* ***Marie O'Regan****, and* ***Daniel LeCloux*** *are Technology Directors for DuPont Displays.*

0362-0972/10/2011-008$1.00 + .00 © SID 2011

lowers the overall material cost when applied with higher efficiency.

When combined, the production of OLED TVs on full-scale equipment using solution processing and nozzle printing will deliver display performance equivalent to evaporation at an overall panel cost (without TFTs) that is reduced by 40–60%, depending on the scale achievable by evaporation techniques.

The Promise of OLED for Television

OLED displays have carried the potential of being an ideal technology for viewing large-format video from their inception. The basic structure of a stack of organic layers on the order of 200 nm thick that is directly emissive immediately invites the concept of an ultra-thin, high-contrast, fast-responding display. Combined with the laboratory demonstration of highly saturated colors and excellent power efficiency, these attributes implied that the development of large-format displays with cathode-ray-tube (CRT) quality and thinner-than-LCD format was simply an engineering challenge.

Additionally, the inherently simpler structure of OLED displays was expected to reduce manufacturing costs for OLED panels as compared to other technologies. Elimination of the light generation, distribution, polarization, and filtration elements of LCD panels was expected to far outweigh the cost of deposition of the organic layers and modification of the thin-film-transistor (TFT) array to support current-driven subpixels.

Commercialization of OLED technology has resulted in the achievement of some but not all of the potential of these displays. Cost and price have remained significantly above the LCD analogs; recent industry reports[1] indicate that the average selling price for OLED modules runs ~3× that of the LCD equivalents.

OLED Material: From Test Coupons to Printed-Display Performance

The authors' company has been working for over 10 years in materials development for use in the solution processing of OLED devices. Core competencies in solid-state materials science, functional polymers, organic and organometallic materials synthesis, film coating, and formulations are all critical in tackling the inherently difficult task of printing organic electronic devices. One of the greatest challenges in manufacturing functional OLED displays is building a deep understanding of the strong interaction between OLED materials and the deposition process. Advances in both materials and process optimization have helped reduce the development cycle time. This cross-functional effort has resulted in small-molecule solution-based materials tailored to the nozzle-printing process that deliver OLED performance acceptable for commercial display applications.

An example of a typical development cycle, from conception of new compositions to integration in active-matrix OLED (AMOLED) displays, is outlined in Fig. 1. Transport, host, and emitter compositions are first tested in single, large-pixel, spin-coated test coupon devices. This platform is used because the devices are relatively simple and fast to prepare for the purpose of rapidly screening new materials. Through a series of experiments, the device architecture and layer-processing conditions of these test devices are adjusted to optimize color saturation, current efficiency, voltage, and lifetime. Color targets correspond to NTSC or sRGB standards so as to maximize the display color gamut. Power consumption is minimized to conserve power and slow the heat- and current-driven degradation of both the OLED and driving transistors. Loss of lifetime of the OLED device, which corresponds to dimming of emission over time arising from chemical degradation of one or more material components, is minimized.

The spin-coated test coupon performance detailed in Table 1 is representative of a current typical material set. A common architecture was employed with identical layer thicknesses for indium tin oxide, hole/electron injection and transport, and cathode layers. Selectively optimizing individual layer thicknesses for each color can improve performance and is possible in the laboratory, but practical manufacture of an AMOLED display requires common layers. Consequently, all testing is performed using a common architecture to better predict real-world display performance. In order to achieve appropriate white balance, the common architecture selected is designed primarily to maximize blue color saturation, efficiency, and lifetime with concomitant reduction in red and green performance.

Each color was run at the luminance and color listed in Table 1, where the luminance values were selected. The data are not projected from accelerated testing. The luminance values were selected to simulate a bottom-emitting display running with a 200-nit white front-of-screen (FOS) brightness with 40% aperture ratio (AR) and 45% transmittance through a circular polarizer used for contrast enhancement. It should be noted that the subpixel luminance needs to be bright enough to compensate for these area and transmission losses. An elevated temperature was used to test the blue in this example because larger AMOLED displays will likely operate above ambient temperature.

New compositions that exhibit improved performance *vs*. incumbent "champion" materials are next tested in printed test devices. Transitioning candidate materials from spin coating to nozzle printing frequently requires substantial adjustments to formulations, architectures, and processing

Table 1: Typical RGB performance using spin-coated test coupon devices is shown. T97 refers to the operating time that has transpired when the luminance output falls to 97% of its initial value when operated at constant current. Similarly, T50, mentioned further on in this article, means the time until a 50% drop. They are measured to assess both the potential for image burn-in (T97) as well as the time until full end-of-life (T50).

Color	Luminance (nits)[a]	Efficiency (cd/A)	Voltage (V)	CIE (x, y)	T97 (hours)	Lifetest Temperature (°C)
Red	900	21	5.8	(0.65,0.35)	800	24
Green	1850	89	3.9	(0.34,0.63)	900	24
Blue	900	6	4.8	(0.14,0.14)	500	32

[a] Simulates 200-nit FOS white with CIE = (0.28, 0.29), 40% AR, and 45% polarizer transmittance.

conditions. Materials that also show improved performance in printed devices are then fabricated into AMOLED displays. Extensive failure-analysis studies are conducted on both spin-coated and printed devices to pinpoint the material(s) in the device stack most responsible for any ensuing performance limitations. The data and understanding are used to conceive new material candidates, which begins the development cycle anew.

Typical nozzle-printed device performance results are shown in Fig. 2. Printed lifetimes are quoted at subpixel luminances that simulate 200-nit FOS white brightness. Even for blue, the most challenging color, lifetime exceeds 30,000 hours and should be sufficient for many display applications, including OLED TV. While, in general, the spin-coated results are indicative of final printed performance, the green material of Table 1 has not of yet been transitioned to a printable formulation. Hence, the green efficiency reported in Fig. 2 is significantly different from that shown in Table 1, as expected for two different materials.

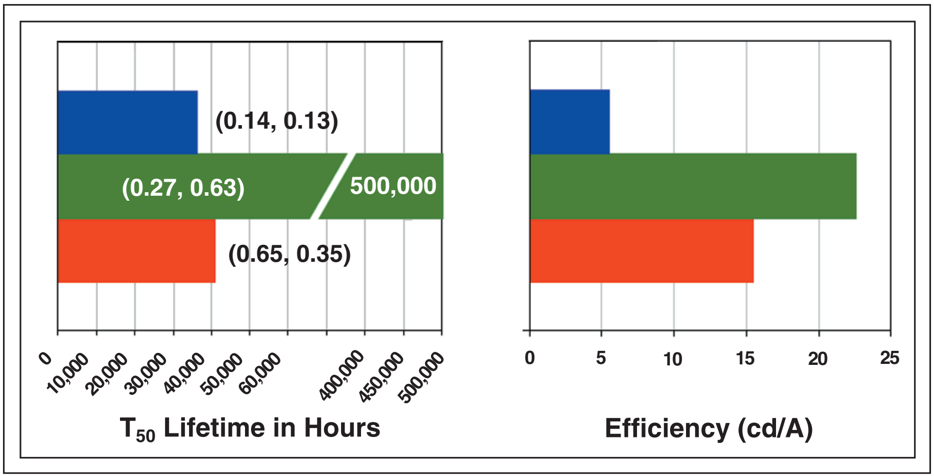


Fig. 2: Shown are printed bottom-emission test devices with no outcoupling enhancement, 200-nit FOS (white-point CIE 0.31, 0.32) with 40% AR, 45% transmission circular polarizer at 100% duty cycle. Lifetime data reported at 20°C.

Cost and Scale

LCDs have driven down cost per square-meter, in part through aggressive increases in the scale of manufacture. Figure 3 shows the relative capital productivity of the typical range of equipment used in the manufacture of TFT-LCDs. In general, equipment cost increases by about 30% for an increase in generation, while glass output increases 50–100%. Fixed cost, maintenance, and facilities costs follow similar trends. OLED manufacturing has had difficulty in following a similar strategy due to technical barriers encountered when scaling up the organic deposition process.

AMOLED displays are almost exclusively manufactured on a smaller glass size than their LCD counterparts. OLED deposition is typically performed on glass sheets cut down after TFT manufacture. This is due primarily to the limitations of the fine-metal-mask evap-

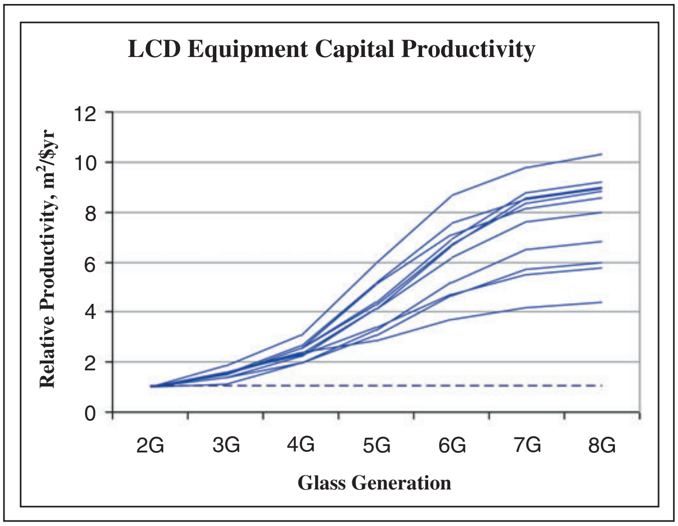


Fig. 3: TFT-LCD equipment capital productivity is compared to glass generation. Glass-area throughput for various types of equipment increases much faster than capital cost, resulting in a 4–10× improvement in capital productivity over the range of Gen 2 – Gen 8.[3]

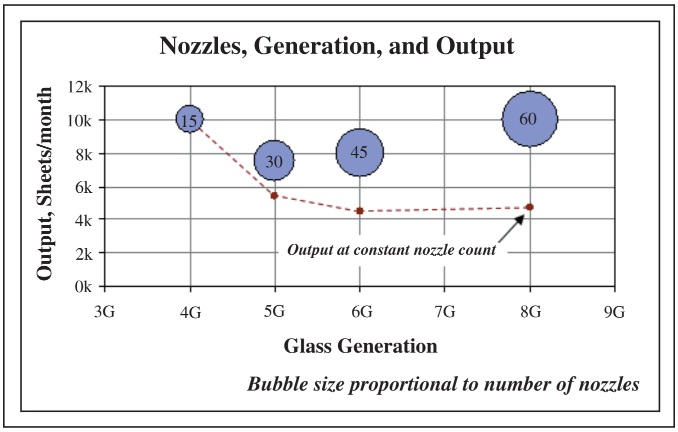


Fig. 4: Nozzle-printer output is shown for multiple generations of glass. Modest increases in nozzle count can maintain printer output in the target range of 7.5–10k sheets/month per printer. Estimates are based on benchmark display sizes of Gen 4 (3.5 in.), Gen 5 (12.1 in.), Gen 6 (17 in.), and Gen 8 (55 in.).

oration process required to pattern the subpixel structure of the OLED. As mentioned above, an alternative to this deposition and patterning process, nozzle printing,[2] has been developed in order to provide a readily-scalable technique for OLED manufacture.

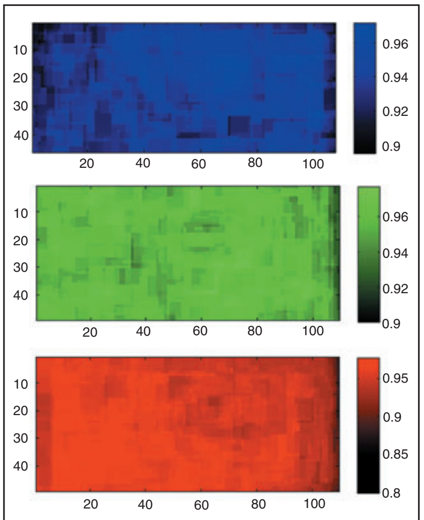
Nozzle printing provides multiple continuous streams of OLED solutions that are drawn across the substrate at high speed using production equipment that Dai Nippon Screen Co. (DNS) developed in partnership with DuPont. The simple control requirements allow excellent uniformity to be achieved. Deposited volume is dependent only on flow rate (which is held constant) and speed, which are both readily controllable by developed technologies. Increasing the scale of the printing equipment is a relatively straightforward engineering task involving the optimization of the number of nozzles, speed, and acceleration of the printing head.

Because printing is a serial operation, the Total Average Cycle Time (TACT) of the equipment is a function of the display resolution and substrate layout as well as the substrate size. Since larger substrates are used to produce larger displays at lower resolution, the number of passes required by the printer does not increase as fast as generation size. Nevertheless, longer scan lengths and increasing scan counts will result in productivity decreases with increasing substrate size if all other parameters are held constant. Consequently, moderate nozzle count increases are planned for larger scale printers as illustrated in Fig. 4. Nozzle printers have been produced in full Gen 4 size with 15 nozzles. A single printer is capable of producing 10,000 sheets per month (benchmark 3.5-in. display) while depositing all three colors simultaneously. Similar printers with 30, 45, or 60 nozzles can maintain a 7,500–10,000 sheet output, as glass size is scaled up through Gen 5, 6, and 8.

An additional consequence of the fundamentally serial nature of the printing process is the potential for non-uniformity of luminance across a display or substrate. The demonstration of the printing-process capability to meet these requirements has been the most significant milestone following the production of the Gen 4 multi-nozzle printer. As previously reported[2] and illustrated in Fig. 5, the short-range uniformity of printed displays produced on this manufacturing equipment has exceeded the performance of commercial LCDs. All other steps required in the process developed by DuPont can be accomplished on standard or modified LCD equipment where the economics of large glass sizes can be applied.

Material Consumption and TACT

The consumption of OLED materials in the panel-manufacturing process plays a significant role in the economics of panel production. Thermal evaporation remains a relatively inefficient deposition technique where the vast majority of the material evaporated is not deposited over the substrate area. Metrics for defining deposition efficiency vary and can lead to confusion regarding actual material cost for panel manufacture. For this discussion, a material efficiency of 100% will be defined as using exactly the amount of material required to cover the substrate area with a layer of the target thickness. For example, if a transport layer with a density of 1.2 g/cm^3 is intended to be coated over the entire active area at a 15-nm thickness and the substrate area is 55,000 cm^2 (Gen 8), the consumed mass of material is compared to $(t \times A \times \rho)$ or $(1.5 \times 10^{-6}\ \text{cm} \times 55{,}000\ \text{cm}^2/\text{sheet} \times 1.2\ \text{g/cm}^3 = 0.1\ \text{g/sheet})$. If more than 0.1 g of material is consumed per sheet processed, the efficiency is less than 100%. It is a useful simplification to maintain this reference for more complex patterning of layers. If an emissive layer is patterned through a fine mask with a target thickness of 30 nm, the same basis can be used to calculate the material consumption; even though the material is required on less than 30% of the substrate area, consumption for that layer will be similar.



Summary

Color	U_{sh}
Blue	0.94
Green	0.94
Red	0.95

Fig. 5: *Uniformity map data from multi-nozzle-printed AMOLED displays demonstrate superior short-range uniformity over production LCD benchmarks (SRU = 0.93).*

Using this reference, the amount of material consumed per layer can be described as the multiple of that which would be required if the theoretical 100% efficiency is achieved. This parameter has the dimensionless units of g/g or the number of grams consumed to deposit a layer over the grams required to coat the entire substrate with a layer of the same thickness. Typical evaporative processes require 5–10 grams of material per gram deposited on the area of the substrate. This parameter is significantly impacted by the evaporator design with classic long-throw, point-source evaporators requiring the highest material waste. Shorter-throw evaporators with linear sources have been demonstrated to reach the 5 g/g metric. Some new evaporator sources claim efficiencies in the 2–3 g/g range, although these efficiencies have not been attempted in production.

Solution-processed material efficiencies vary depending on the deposition technique employed. For unpatterned coatings, such as hole-injection layers, efficiency is largely determined by the ratio of slot coater priming to coating time. Priming of the coating head is accomplished by depositing material on a priming roll in order to wet the die lips and prepare the die to deposit a defect-free film. Typically, the priming of the coating head is accomplished for a fraction of the time required for coating the substrate, so efficiencies in the range of 1.1–1.3 g/g are readily achieved.

Printing efficiency is more complex and interacts with other printing parameters. Nozzle printing employs a continuous flow of ink through the printing orifice and results in material waste when the printing head is accelerating or decelerating off of the substrate. The optimization of scan time and material efficiency is a key part of nozzle-printing-equipment engineering.

Acceleration of the nozzle print head is typically constrained by the mechanical

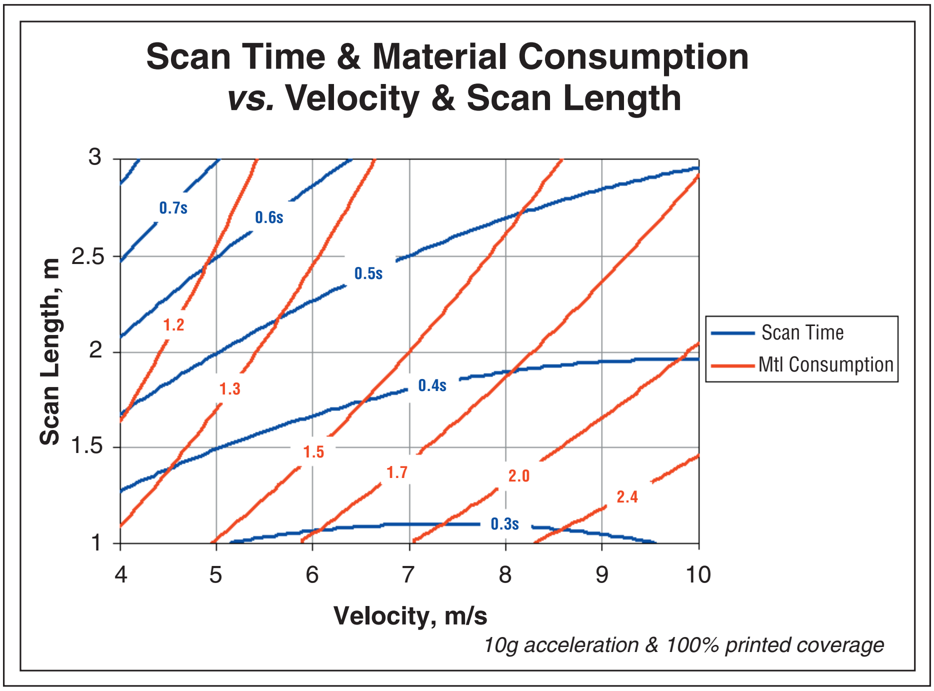


Fig. 6: *Design parameters for nozzle printing require balancing optimum TACT with material efficiency to deliver the lowest total cost.*

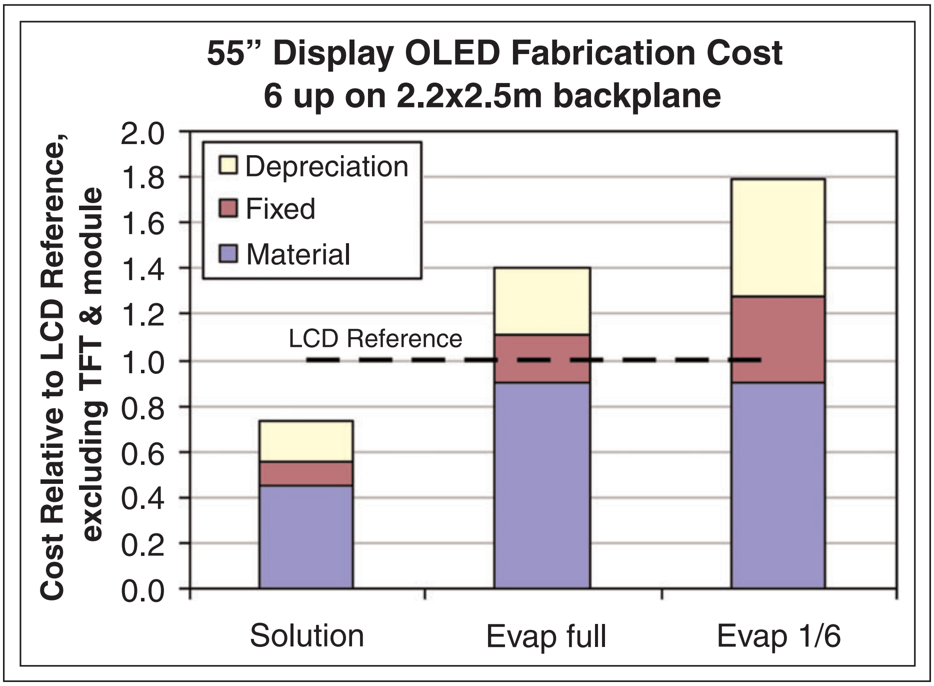


Fig. 7: *A cost comparison for evaporation shows full and cut-down substrates. Reference LCD comes from third-party industry cost models provided by iSuppli and DisplaySearch.*

system employed to drive the head traverse. For a given acceleration, an optimum speed can be established for any given scan length that will provide the shortest scan time:

$$t = (2v/a) + (L/v),$$

$$\mathrm{d}t/\mathrm{d}v = (2/a) - \left(1/v^2\right)$$

$$v_{\text{optimum}} = (La/2)^{1/2},$$

where t is the scan time, v is the head velocity, a is the head acceleration, and L is the scan length. Similarly, the material consumed *vs.* printed (g/g metric) can be estimated based on the total scan time over the time spent printing. This is simply expressed as

$$\begin{aligned} c &= \left(t_p + t_a\right)/t_p \\ &= \left[(L/v) + (2v/a)\right]/(L/V) \\ &= 1 + \left(2v^2/La\right) \end{aligned}$$

where c is the material consumed *vs.* theoretical, t_p is the printing time, and t_a is the acceleration time.

From the above equation, it is clear that an increase in acceleration and/or scan length will improve efficiency and a decrease in scan velocity will improve efficiency. Any printer optimized for TACT alone will give a consumption of 2 g/g since cycle time is optimized when $t_p = t_a$. This leads to a fundamental trade-off in printer design to find a working value of scan velocity that will deliver acceptable TACT at good efficiency. For the Gen 4 printer configuration, the operating point has been selected at 10 g acceleration and 5-m/sec velocity, giving 1.6 g/g scan consumption (for full-sheet coverage) with a scan time of about 300 msec.

The summary of these material-consumption comparisons is that while evaporated layers typically consume 5–10 g of material per gram of material needed to coat the substrate, solution-processed layers consume 1–1.3 g for coated layers and 0.6–2.0 g for printed layers, depending on the selected architecture. For typical RGB printed layers, consumption of the emissive material is less than 1 g/g since the printed area is significantly less than the substrate area (Fig. 6).

Cost of Manufacture

By combining the material, capital, and fixed-cost assumptions outlined above, projections of manufactured cost for the OLED panel can be generated. The following charts compare projections for evaporation on cut-down substrates as well as projections that assume evaporation can scale to the full-sheet processing. Costs are for OLED fabrication only and exclude TFT and module components.

Cost of manufacture for nozzle-printed OLEDs is projected to be about 30% below the incumbent LCD cost and almost 50% below equivalent evaporated panels, as shown in Fig. 7. The cost savings are a result of lower material consumption, lower capital cost, and lower fixed cost due to reduced maintenance and tooling required for printing equipment. When costs of full Gen 8 solution processing are compared to cut-down processing for evaporation, the differential increases to almost 60%.

"Solutions" for OLED Manufacturing Costs

OLED-TV manufacture can be practically accomplished through solution processing. Material developments have delivered performance that meets the threshold for television requirements and process developments can meet manufacturing cost targets. Nozzle printing is a flexible technology that uses materials efficiently and can be scaled to Gen 8 glass size to enable OLEDs to enjoy the same economies of scale that have enabled LCDs to become the dominant display technology. These advancements will allow the myriad benefits of OLEDs to be delivered while significantly reducing manufacturing costs compared to LCD incumbents.

References

[1] "Q2 '11 Flextech Alliance Business Conditions Report," DisplaySearch, p.18 (July 2011).

[2] R. Chesterfield *et al.*, "Solution-Coating Technology for AMOLED Displays," *Information Display* **27**/1, 24-30 (2011).

[3] Data aggregated from industry LCD cost models and vendor quotations. ■

OLEDs in Transition

The OLED industry is in the midst of change – from passive to active matrix and from small to larger sizes. This change is being driven by a significant amount of investment in active-matrix OLED manufacturing facilities – with the ultimate goal being to compete in the TV market. While the industry attempted to commercialize OLED TV in the past, the cost structure and productive capacity were not ready. This time, the pieces are coming together for a successful market entry.

by Paul Semenza

IN 2011, total organic-light-emitting-diode (OLED) display shipments are expected to reach 180 million units, which represents a growth rate of 61% over 2010. Unit growth is being driven by active-matrix OLED (AMOLED) display shipments, whose growth rate increased from 103% in 2010 to 136% in 2011, while passive-matrix OLED (PMOLED) display shipment growth fell from 20% to 9%. AMOLED-display growth is expected to again surpass 100% in 2012, as AMOLED-display manufacturing capacity undergoes significant expansion. After almost doubling in 2010, total OLED-display revenues are expected to nearly triple in 2011, reaching $4.5 billion. Revenues are expected to more than double in 2012 and to exceed $20 billion by 2016. Even more so than in the case of units, active matrix dominates OLED-display revenue growth. Driven by unit growth as well as increases in average screen size, AMOLED-display revenues will grow more than tenfold between 2010 and 2013, from $1.25 billion to $12.9 billion. Growth in PMOLED-display revenues has been slowing and is likely to peak by 2015 at just over $400 million, as active-matrix LCDs (AMLCDs) and OLED displays take share from passive matrix.

Mobile Phones a Successful Platform for AMOLED Displays

Mobile-phone displays remain the core application for OLED displays, but the composition is shifting from secondary to primary displays as AMOLED displays have entered mass production, and as flip (or clamshell) type phones continue to lose share to larger, single-display smartphones (Fig. 1). Samsung-branded smartphones have been the dominant application for AMOLED displays. The display size has increased from 3.3 to 4.0 in. in 2010 models to 4.0 to 4.5 in. in 2011 models. At the IFA show in Berlin in September, Samsung showed its new Galaxy Note smartphone, having a 5.3-in. AMOLED display. Nokia also expanded its AMOLED-display product portfolio in 2011, with six smartphone models using AMOLED displays between 3.5 and 4.0 in.

The next promising application for AMOLED displays is the amusement market, including portable game machines. There are high expectations for PSP Vita, the new portable game machine with AMOLED displays that

***Paul Semenza** is Senior Vice-President, Analyst Services, with the market research firm DisplaySearch. He can be reached at paul.semenza@displaysearch.com.*

Fig. 1: Mobile-phone main displays have emerged as the leading application for OLED displays, as the market has shifted to smartphones and away from flip phones, and as AMOLED-display production has ramped up. Source: DisplaySearch Quarterly OLED Shipment and Forecast Report.

0362-0972/10/2011-014$1.00 + .00 © SID 2011

Sony recently announced. AMOLED displays for PSP Vita are expected to start shipping in Q3 '11. In the digital-still-camera (DSC) market, another promising application for AMOLEDs, shipments started to increase in Q4 '10. However, as can be seen in Fig. 2, on a unit basis, no other application is expected to come close to mobile-phone displays as a source of demand for OLED displays.

The main application for PMOLED displays, mobile-phone sub-displays, has been stagnant because of the surging popularity of smartphones without sub-displays. Japanese PMOLED-display suppliers, such as TDK and Pioneer, have decreased sub-display shipments, while Taiwanese and Chinese PMOLED-display makers are increasing shipments for home appliances and other applications.

The rapid growth of mobile-phone displays will be the primary driver behind OLED-display revenue growth for the next few years (Fig. 3). After 2014, lower unit growth and expected price declines will result in a slowdown in revenue growth. At that point, we expect to see TV emerge as the key driver of revenue growth for OLED displays. While expectations are high for OLED TVs in the near term, it will take a few years for advanced-generation AMOLED-display factories to come on line, increase yields, and drive down costs. Along with the ability to make 30+ in. TV panels, these new factories will also enable mass production of 5–15-in. panels for mobile PCs. It is possible that we could see tablet PCs with AMOLED displays commercially available in 2012. At the IFA Conference, Samsung showed a Galaxy Tab with a 7.7-in. AMOLED display, but withdrew the sample during the tradeshow.

Market Growth Driven by Production

In 2010, Samsung Mobile Display (SMD) shipped 45.6% of all OLED displays and 99.3% of AMOLED displays; in the first quarter of 2011, SMD increased its share of shipments to 51.5% and 99.9%, respectively. Because of the company's lead in the higher-value AMOLED technology, Samsung increased its share of revenues from 81.3% in 2010 to 88.3% in Q1 '11. It is rare in the display industry to see anywhere near this level of dominance by one company in a technology category. There is the possibility that a first-mover advantage exists in AMOLED technology: depreciation as a share of total cost is approximately twice that of TFT-LCDs, meaning that the first to fully depreciate capital expenditures will have a significant cost advantage. However, given the fact that Samsung is vertically integrated in mobile phones, TVs, and other products, some OEMs are reluctant to adopt AMOLED displays as long as SMD has such dominance. So, in order for the OLED-display market to grow significantly, other suppliers are clearly needed in the market.

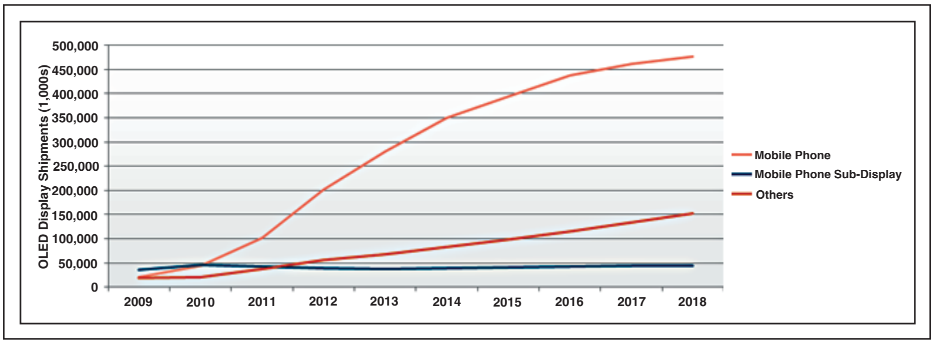


Fig. 2: Mobile-phone main displays will continue to represent the largest application for OLED displays in unit terms. Source: DisplaySearch Quarterly OLED Shipment and Forecast Report.

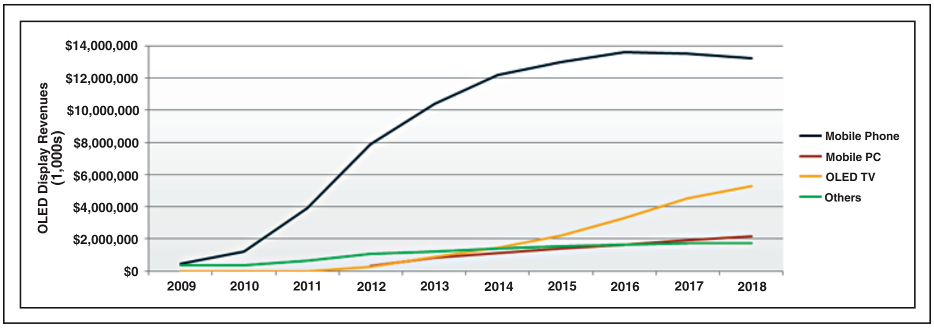


Fig. 3: Mobile-phone main displays will dominate revenues for OLEDs for the next few years, but after 2014, revenues from TV will grow much faster, and mobile PCs will also become a significant application. Source: DisplaySearch Quarterly OLED Shipment and Forecast Report.

For the next few years, however, SMD is likely to continue to be the leading supplier of OLED displays. The company started mass production at the first Gen 5.5 AMOLED fab in June 2011. It is expected to expand its Gen 5.5 AMOLED-display lines and ramp-up Gen 8 lines for large-sized AMOLED panels. AMOLED panels for mid- or large-sized applications, such as mobile PCs and OLED TVs, are forecast to start shipping in 2H '12 when SMD expands its production capacity or ramps up large-sized AMOLED-display production, although technical uncertainties remain both in backplane design and organic materials deposition.

After suspending production in the middle of 2010, LG Display (LGD) is planning to resume AMOLED-display production on its Gen 4 line and was expected to restart shipping AMOLED displays for mobile phones in Q2 '11. However, LGD's main focus for AMOLED displays is the TV market. It is planning to ramp up a Gen 8 AMOLED-display fab in 2012. The company has been pursuing white OLEDs with color filters rather than RGB emitters and is developing IGZO-based white AMOLEDs with color-filter–on–TFT technology.

In Taiwan, AUO and CMI have smaller fabs (Gen 3.25) that are in mass production or are planned to be in 2012; these fabs are limited to producing mobile phone and other small-to-medium displays. AUO is also preparing its Gen 4 fab in Singapore to produce AMOLED displays.

In China, IRICO is building a Gen 4 AMOLED-display fab in Foshan-Shunde, which could begin mass production in late 2012. On August 12, the BOE Group made a surprise announcement that it will invest \$3.5 billion to build a Gen 5.5 AMOLED-display production line in Ordos, a city in the Gobi desert in China's Inner Mongolia Province, in exchange for rights to extract coal from the resource-rich province. It will be a significant challenge to operate an AMOLED-display fab in such a remote location, without any supply chain or plentiful water supply, and for BOE to make the leap into Gen 5.5, the leading edge of AMOLED-display production.

All of the Japanese producers of AMOLED displays have exited the market or stopped production, including, most recently, Sony, although the company still has some capacity. Ortus, a joint venture of Toppan Printing and Casio, has also been developing pilot production for AMOLED displays. Other Japanese companies that have historically had development or produced AMOLED displays include Epson, Hitachi, Panasonic, Sanyo, Sharp, and Toshiba.

Taking all of these developments into account, it is clear that there will be a significant increase in overall AMOLED-display manufacturing capacity (Fig. 4). This is a crucial development for the industry, as it will give customers the confidence to adopt the technology and allow for multiple applications to be pursued. It will also provide the experience needed to tackle the significant challenges in scaling to larger substrate sizes.

Ongoing issues for scaling AMOLED-display production beyond the existing Gen 4 lines center on backplane manufacturing and organic material deposition.[1] The latter can be addressed by creating the backplane on a full substrate and then cutting the substrate into smaller pieces for organic materials deposition. For the backplane, most of the focus has been on low-temperature polysilicon (LTPS), but the challenges of scaling this technology beyond Gen 4 have led to continued development of alternative technologies such as oxide semiconductors. In addition, work continues on using a-Si TFTs, the dominant form of active-matrix backplane technology, in AMOLED displays. At SID 2011, IGNIS and RiTdisplay demonstrated a-Si TFT AMOLEDs, using architectures and technologies developed by IGNIS.

In PMOLED-display manufacturing, RiTdisplay, SMD, Pioneer, and TDK were the original market leaders, but SMD moved its focus to AMOLED displays at the end of 2010, and Pioneer has been losing share as demand in mobile phones and automotive markets has been declining. At the same time, WiseChip, which acquired Univision's OLED business, took the lead in the first quarter of 2011, and Visionox has been steadily increasing its market share; both companies have had success with mobile phones for Asian markets, as well as appliances and other applications.

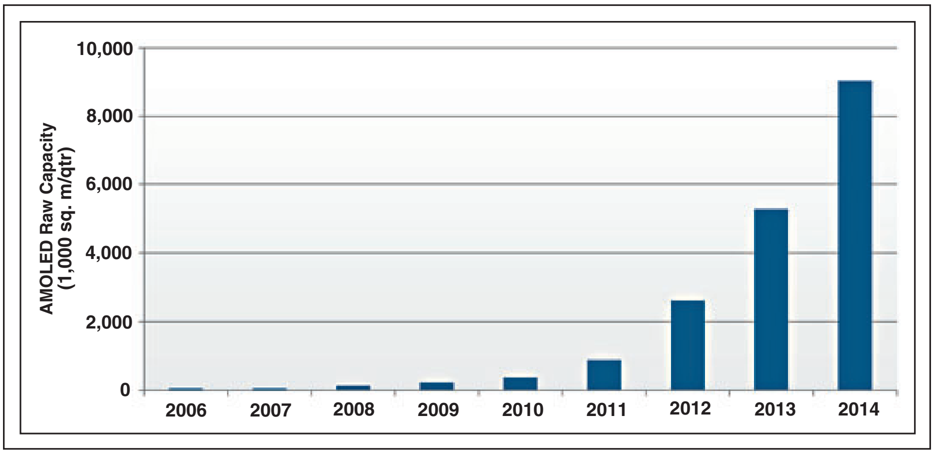


***Fig. 4:** Led by Samsung Mobile Display (SMD), AMOLED-display manufacturing capacity is expected to grow tenfold over the next 4 years, as the industry moves beyond Gen 4 fabs. Source: DisplaySearch Quarterly FPD Supply/Demand and Capital Spending Report.*

This Time, Will Things Be Different?

The OLED-display market has suffered from an excess of hype and a deficit of real products. From picture frames to TVs, products have been introduced without the ability to produce them in volume at a cost that would allow them to compete with TFT-LCDs. At the same time, the incumbent technology has been improving, using LED backlights to reduce thickness and improve color gamut, as well as novel pixel architectures to improve viewing angles. Thus, OLED displays face a more challenging competitive environment than a few years ago. Why might things turn out differently this time?

The biggest factor is the ongoing investment in AMOLED-display manufacturing. The demand for displays is huge and growing – in 2010, OLED displays represented just over 0.1% of the total display market, measured by area. The challenge for AMOLED displays has been to build out manufacturing capacity that would allow the technology to serve multiple applications, particularly the key large-area products: mobile PCs, desktop monitors, and TVs. To date, there has been a "chicken-and-egg" problem – given the relative immaturity of OLED technology, its cost structure is higher, but given the competitive nature of the computer and consumer electronics markets, AMOLED technology needs to be competitive with TFT-LCD pricing.

At the same time, the inherent simplicity of OLED technology and the small amounts of materials needed for manufacturing strongly suggest that OLED displays should be cheaper to produce in high volumes. But it still takes a first mover to invest in state-of-the-art production and to work with equipment suppliers to surmount the barriers to large-sized AMOLED-display production. What we are seeing at present is a combination of market acceptance in mobile devices, combined with the beginning of a sustained series of investments. If realized, these investments will enable OLED-display technology to make the transition to a mass-market display technology.

References

[1] For a discussion of developments in AMOLED-display manufacturing, see P. Semenza, "Can OLED Displays Make the Move from the Mobile Phone to the TV?" *Information Display* **7&8** (2010). ■

Beyond Amorphous-Silicon: New Developments in High-Mobility Backplanes

New advances in laser-crystallization technology are enabling larger liquid-crystal and OLED displays.

by Ulrich Hausmann and David Knowles

CONSUMER DEMAND for mobile devices, tablets, and televisions is driving the need for new, more advanced displays. In fact, in devices such as the iPhone and the Samsung Galaxy phone, the display has become one of the key differentiators. These advanced displays are characterized by high pixel densities or by the use of organic light-emitting-diode (OLED) materials. They depend on thin-film-transistor (TFT) backplanes that are typically fabricated from low-temperature polysilicon (LTPS) instead of the more common amorphous silicon. Polysilicon provides much higher electron mobility, but creating it has been one of the more challenging manufacturing steps in the display process. The laser-annealing equipment required for LTPS has garnered a reputation for high cost and variable yields.

Recently, there have been a number of significant advances in LTPS backplane technology. The past few years have seen greater competition among laser-annealing equipment suppliers, leading to a number of innovations. There are also several alternative approaches under development to replace polysilicon. This article will review the progress of both laser annealing and alternatives, which together promise to greatly reduce the manufacturing complexity and speed the adoption of advanced displays. Related key trends and driving factors to be discussed include ultra-high-resolution LCDs, increasing LCD frame rates and display sizes, and the explosive growth of the tablet market.

David Knowles *is the Vice-President and General Manager of the TCZ Display Products Group at Cymer, Inc.* ***Ulrich Hausmann*** *is the Director of Marketing and Applications and can be reached at ulrich_hausmann@tcz.com.*

Ultra-High Resolution, Higher Frame Rates, and Larger Sizes for LCDs

As everyone knows, in 2010 the huge success of Apple's iPhone 4 fundamentally altered the smartphone market by capturing an unprecedented market share. A key feature of the iPhone 4 is its 3.5-in. Retina display with a high resolution (960 × 640 pixels or 326 pixels/in.) that shows very sharp clear images and provides a comfortable viewing experience with clarity rivaling that of print media. LTPS technology, with its very high mobility of approximately 100 cm^2/V-sec, enables such performance by reducing the transistor size in the display's active area. This compares very favorably over amorphous-silicon technology with a mobility on the order of 1 cm^2/V-sec. This allows for a larger aperture ratio, which is very important for display brightness. The large aperture and low-bus-line loading structure of LTPS also helps to minimize power consumption, which is critical for smartphone displays.

Attaining higher frame rates for larger displays and for driving high-speed OLED displays will require the same high-mobility transistors and low-resistance bus-line technologies required for smartphones. LCD- and OLED-TV development is also demanding faster switching speeds and smaller TFTs because increasing the frame rate in LCD televisions is the key to improving motion and minimizing blur, as well as to supporting new 3-D media applications. These market objectives have pushed frame rates from 120 Hz to 240 and 480 Hz. Driving LCDs at these higher frame rates becomes more difficult due to the inherent switching speed of the liquid-crystal material. OLED technology is considered a strong display candidate for 3-D TV because of its fast response time, which reduces image cross-talk during 3-D switching. This enables a much more comfortable viewing experience.

Explosive Growth and Competition in the Tablet Market

Growth in the tablet market took off in 2010, with all indications showing signs of accelerating growth in 2012 and beyond. The pixel density of current-generation tablets is about 130–150 pixel/in., a range in which amorphous-silicon transistors are considered a suitable array backplane technology because of low cost, maturity of the process, and large production capacity. However, because low power consumption is a critical requirement for tablets, and competition is already fierce, new display technologies are likely to be important factors in next-generation tablets.

0362-0972/10/2011-018$1.00 + .00 © SID 2011

The trend in tablet displays is projected to move toward higher resolution, small border size, and low power consumption, so high-performance, high-mobility transistors will be key enabling technologies.

Key Technology Shift #1: OLEDs Have Moved into Mass Production

A key technology development of last year was the breakthrough of OLED into mass production, which gave display makers a viable production alternative that offered superior color gamut, high contrast ratio, a wide viewing angle, and fast response times. OLEDs were an important factor in the success of the Samsung Galaxy line.

OLED displays offer a number of advantages compared to LCDs, both for manufacturers and consumers. One major advantage is the ability of OLEDs to provide richer, vibrant colors without the need for a backlight, liquid-crystal material, or polarizer films, thereby simplifying the design and reducing manufacturing costs (see Fig. 1). OLEDs' speed advantage is particularly helpful in implementing 3-D functionality.

OLEDs can provide nearly perfect image quality, but have a few drawbacks. Compared to LCDs, OLED displays have to date had lower resolution and a larger border size. Furthermore, because OLEDs are current-driven devices, the display brightness is very sensitive to the driving transistor characteristics. Non-uniformity in the display, which is known in the industry by the Japanese word "mura," has been a challenge in moving OLEDs to volume production. Mura has been linked to many process steps, including laser crystallization, non-uniformity of CVD film, doping concentration, activation annealing, photolithography, and etching. Great progress has been made in all of these areas, and there are now several display makers that offer OLED products.

Key Technology Shift #2: LTPS Has Become the Industry Standard

As discussed, amorphous-silicon has a very limited electron mobility (< 0.5 cm^2/V-sec), which makes it unsuitable for high-mobility applications. In addition, amorphous silicon tends to degrade under the high-current loads required by OLEDs, leading to lifetime issues and image sticking. It has therefore mostly been abandoned for high-volume OLED production.

LTPS is now the most mature and highest performing candidate for advanced display manufacturing and is the standard approach for mass production of both high-resolution LCD and OLED displays. LTPS is created by irradiating amorphous silicon with a laser pulse, melting it in a very short time period (<100 nsec). After the pulse, the silicon film forms many small crystals as it solidifies.

Alternative Technology Approaches: Metal-Oxide TFT or Solid-Phase Crystallization

Although LTPS has become the industry standard, there are several other transistor technologies that have been developed as alternatives to laser crystallization. The two most promising are metal-oxide transistors and solid-phase crystallization.

Metal-oxide TFT development has been an active research area over the last several years. The most mature material for metal-oxide transistor active layers is indium-gallium-zinc-oxide (IGZO). It has a mobility of 5–15 cm^2/V-sec, significantly higher than amorphous silicon. A 70-in. 240-Hz 3-D TV using metal-oxide TFTs was exhibited by Samsung at SID's Display Week in 2011. Metal-oxide TFTs are also a candidate for medium-sized displays, such as tablets and laptop monitors. The metal-oxide TFTs have a smaller transistor area than amorphous-silicon TFTs, which should increase the aperture ratio and reduce the power consumption. Overall, metal-oxide TFTs offer performance and capital cost in between amorphous and polysilicon.

One challenge facing metal-oxide TFTs as they enter mass production for advanced LCDs is that the TFTs are sensitive to light. This can lead to transistor threshold-voltage shifts when the active layer is under light exposure. A protective layer is needed to cover the metal-oxide transistor to prevent

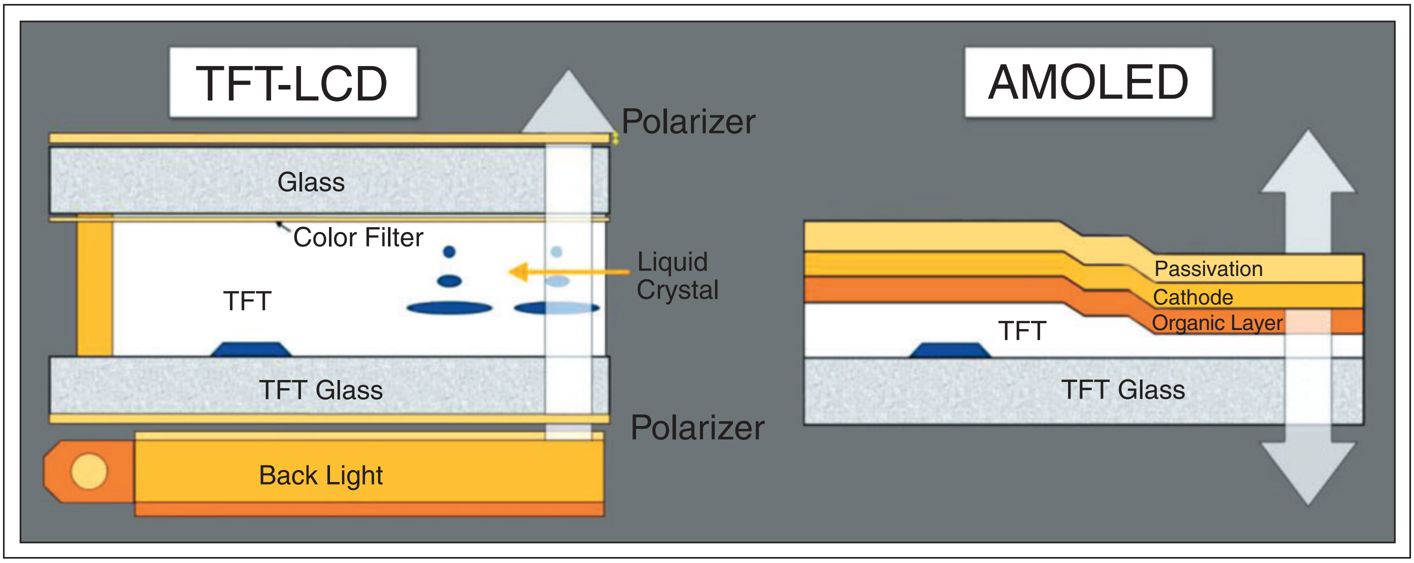


Fig. 1: The TFT-LCD stack at left requires more elements (for example, a backlight) than the OLED stack at right. Source: Cymer, Inc.

this problem, requiring an additional photomask process. Several display makers are currently planning the pilot production of LCD devices using metal-oxide TFTs, so the practical limitations of this technology should soon become clear.

Metal-oxide TFTs may be faced with larger challenges in extending to OLED displays. OLED TFTs require higher current levels, which can degrade the amorphous metal-oxide material over time. This can lead to a shift in the threshold-voltage levels, and also to image sticking if there is differential aging of pixels due to static images. The proposed solution is to use compensation circuits, similar to LTPS TFTs but, as stated previously, the transistor size must be larger due to the lower electron mobility. This will reduce the aperture ratio and brightness for the most common bottom-emission OLEDs. Metal-oxide TFTs are also n-type transistors, in contrast to the p-type transistors of polysilicon. When used to drive OLED pixels, n-type transistors can cause faster degradation of OLED brightness and image sticking. One solution is to implement a reversed-stack OLED structure, but this can lead to low emission efficiency (< 60% of normal).

Solid-phase crystallization (SPC) is an older approach that uses rapid heating of the glass substrate in a furnace to convert the amorphous-silicon coating to polysilicon without melting. The furnaces typically produce high temperatures (>600°C) for several minutes, which can lead to glass deformation. The SPC process has been relatively slow. One approach to speed the process is to add trace amounts of metal (such as nickel) to speed the process. Despite the potential cost advantages compared to that of laser crystallization, SPC is rarely used in mass production due to difficulties with TFT leakage currents and threshold-voltage shift. The weakness of SPC is its lower mobility compared to LTPS. It requires large compensation circuits to overcome the hysteresis effects, which, in turn, lead to significant limitations for high-resolution displays. SPC is also considered difficult to extend to Gen 6 and Gen 8 glass sizes due to glass softening and sag at high temperatures.

Overcoming Traditional Challenges in Laser Crystallization

With metal-oxide TFTs still in development, and SPC not widely adopted, LTPS continues to be the dominant method to produce high-performance transistors. However, there have been significant challenges in scaling LTPS to volume production.

Successful laser crystallization requires precise control of the process to assure uniform crystallization, high throughput, and low operational costs. The most widely used process, excimer-laser annealing (ELA), uses a high-power, pulsed excimer laser to melt a thin line of silicon. A stage moves the silicon-coated glass substrate under the beam, while the laser is operated at a high pulse rate, processing the glass substrate with a series of pulses. To ensure uniformity of the crystallization process, precise and consistent beam control is required. Such control is vital to control stage timing and positioning, as well as laser power, beam uniformity, and focus. While it is widely used in mass production today, ELA has historically delivered relatively low throughput. The beam length was limited, requiring multiple passes to process a single glass sheet. ELA also has had a relatively small process window, which can lead to polysilicon non-uniformities if conditions wander away from the process center. As discussed in the following sections, today's fourth-generation systems show significant progress on both throughput and process robustness, driven by improvements in laser and optical technology.

Higher Laser Power and Beam Stretching Provide Greater Throughput

The excimer laser is the heart of the ELA system, so system productivity is determined by the amount of power the laser can provide. In 2008, the conventional power of a commercial ELA system was limited to 300 W; in comparison, the newest systems now operate with up to 900 W of laser power. Cymer/TCZ achieved this 3× gain in laser power by introducing a MOPA laser, first developed for semiconductor photolithography. (The development of the ELA system with MOPA technology was completed and the first system launched in 2009. The MOPA architecture provides a more stable process window and reduces the running cost at the same time.) A MOPA excimer laser consists of a master oscillator (MO) chamber and a power amplifier (PA) chamber. The MO is responsible for establishing optimal optical parameters, while the power amplifier (PA) maximizes pulse energy (and therefore output power). The net result is an optical architecture that generates much higher power levels than a single chamber system, with excellent optical performance parameters and stability.

Beam length is the second critical factor for increasing the throughput of ELA systems. All ELA systems use a highly asymmetrical beam: narrow in one dimension (5–400 μm, depending on the equipment supplier) and long in the other. The longer the beam length, the fewer passes are needed to process large substrate sizes. In 2008, the state of the art was 465 mm. Today, ELA systems are available with beam lengths up to 750 mm, which allows a Gen 5.5 substrate (1300 × 1500 mm) to be processed in only two passes. It should be noted that beam length and power go hand in hand. Since the process energy density remains the same, a longer beam requires higher laser pulse power. Additionally, the repetition rate of the laser was increased to further augment productivity.

Plans are already in the works for ELA systems supporting up to Gen 8. The challenge for making a practical Gen 8 crystallization system is to increase the throughput. There are several concepts in development, including combining multiple lasers and optics to expose the substrate in two passes (see Fig. 2). The stage size increases for Gen 8, and there are challenges in handling such large substrates, but these have all been solved in current Gen 8 amorphous-silicon fabs. There is no inherent limitation in scaling the ELA technology to Gen 8, and Gen 8 systems should be available in the near future for OLED-TV products.

The Challenge of Providing Uniform Polysilicon for OLEDs

The biggest challenge for laser-crystallization systems today is to improve the uniformity of the polysilicon. This is made even more necessary by the unique requirements of OLEDs: in an LCD, the pixel is voltage-controlled, while OLED pixels are current-driven. TFTs that are required to deliver continuous current are much more sensitive to the underlying electrical properties of the polysilicon. This places tighter requirements on the uniformity of the polysilicon in order to ensure a uniform display. Lack of uniformity in the underlying polysilicon translates to TFT variation, which is then seen as visible mura. One solution for overcoming mura is to include a compensation circuit for each pixel that corrects for pixel-to-pixel TFT variation. Compensation

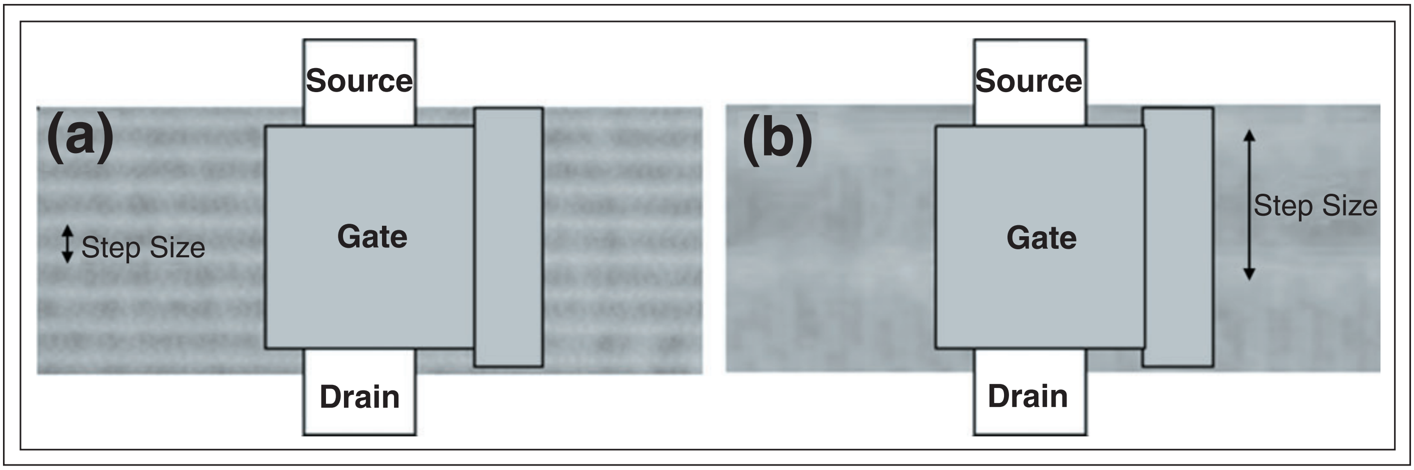


Fig. 2: Top-view illustrations of a transistor located on polysilicon that show (a) small step size (1.5 μm) and (b) large step size (~10 μm). Source: Cymer, Inc.

increases the TFT threshold-voltage margin and improves production yield. A key drawback of compensation is the difficulty of making high-resolution displays (greater than 300 pixel/in.) due to the physical space in the pixel needed for the circuit. The most promising approach for increasing resolution and reducing border size is to minimize the non-uniformity of the array backplane during laser crystallization, so as to use fewer transistors in compensation.

Laser-crystallization processes are carefully designed to avoid scan mura, which can be created by shot-to-shot variations of the laser. Scan mura can be seen as small variations in the polysilicon crystal structure and surface roughness. As previously discussed, display makers have created complex compensation circuits in each pixel to correct for scan mura, but the fundamental goal is to improve the laser-beam uniformity to the point that such compensation can be greatly simplified or entirely removed. In pursuit of that goal, Cymer/TCZ has developed thin-beam ELA (TB-ELA) technology that uses a small scan pitch (1–4 μm) to produce better transistor uniformity than conventional ELA (which typically uses a 10–20-μm scan pitch). Figure 2(a) shows a top view of a transistor located on an LTPS formed by using a step size of 1.5 μm. The transistor channel covers an area crystallized by a series of laser pulses, so that the TFT electrical properties are determined by the average of the pulses. Figure 2(b) shows the same view for the case of a larger step size (10–20 μm), where the TFT channel occupies the area crystallized by only one or two laser pulses. The larger step size results in less averaging, leading to increased TFT variation due to pulse-to-pulse variations.

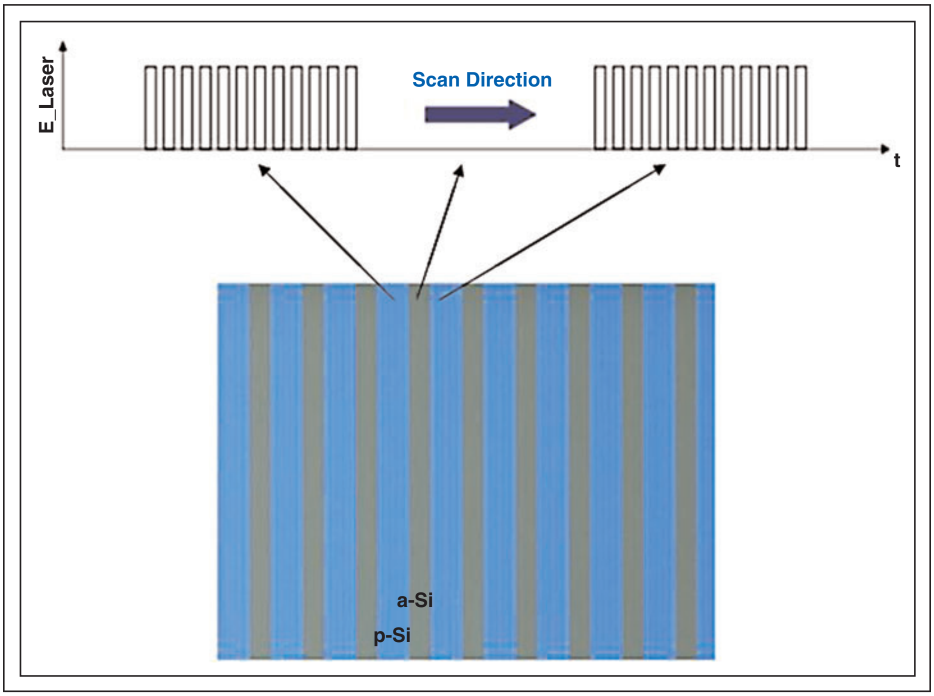


Fig. 3: A laser scan using the stripe mode selectively anneals the silicon only in the transistor area. Source: Cymer, Inc.

Future Improvements in Laser Crystallization for the OLED-TV Market

OLED TV is considered by many to offer the best performance capabilities for next-generation TV systems. It is also expected that OLED process yields will continue to improve and that OLED material cost will continue to fall. In addition, OLEDs have fewer components (such as backlights and optical films). OLED TV should quickly become cost competitive with LCD TVs.

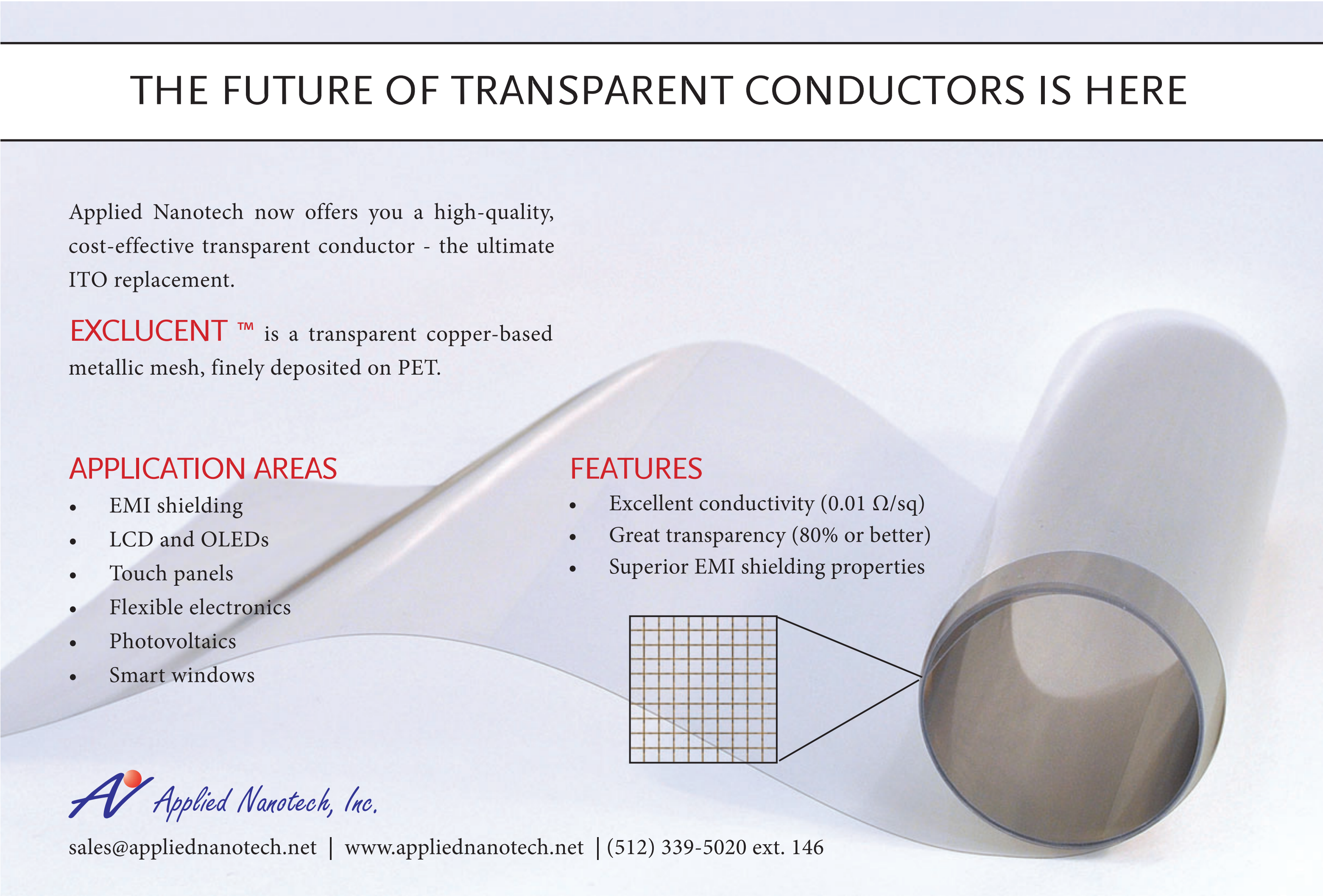
However, as TV glass sizes continue to increase, scanning the entire substrate with a laser could become quite expensive. Several ELA equipment suppliers have developed a stripe mode to reduce the costs of processing larger substrate. Figure 3 illustrates the concept of stripe mode, in which the laser selectively scans the glass, processing only the locations that will be occupied by transistors. As an example, for a 55-in. OLED-TV product with a 150-μm irradiation area and a 630-μm pixel length, the running cost with stripe mode could be reduced by up to 75%.

Display manufacturers are facing a dynamic marketplace that is full of opportunity, but also full of challenges in terms of improving performance and function while increasing production volumes and reducing costs. A future migration to OLEDs will improve display brightness, speed, and pixel density, but also place new demands on manufacturers.

Recent market trends demand a fast ramp-up of TFT technologies that can replace the low electron mobility of amorphous silicon with materials of higher electrical efficiency. Several options are available or under development, including metal-oxide TFTs, SPC transistors, and LTPS.

To cope with this changing landscape, display manufacturers need production platforms that can handle the full spectrum of advanced LCD and OLED technologies. The process must deliver high throughput and be scalable to handle larger display sizes. In addition, display makers need platform stability, process consistency, and high reliability.

Today, laser-crystallization systems are providing very-high-quality polysilicon, and this process has become the current manufacturing standard for advanced LCD and OLED displays. Recent improvements in laser-crystallization technology have improved the yield and reliability of the LTPS process. ■



THE COMPETITION IS GOING TO BE INTENSE.

Nominations are now open for the SID Annual Display of the Year Awards.

The year's hottest displays, display applications, and components. They'll all be competing for SID's annual Display of the Year Awards. So get creative and tell us why your exciting, innovative product picks should be selected.

Submit your contenders today for the Display of the Year Awards. Remember, it's the industry's most prestigious honor, given annually by the Society for Information Display (SID). SID members and non-members alike can nominate one or more products, choosing from any of those introduced into the market during this calendar year.

For more information, or to submit a nomination, visit: http://www.sid.org/AboutSID/Awards/DisplayoftheYearAwards.aspx. All nominations must be received by December 31. The Display of the Year Awards are to be announced and presented at Display Week, the Annual SID International Symposium, Seminar and Exhibition to be held in Boston, Massachusetts, June 3rd to the 8th, 2012.

Categories:

Display of the Year Award
Granted to the display with the most novel and outstanding features.

Display Application of the Year Award
Granted for a novel and outstanding application leveraging a display.

Display Component of the Year Award
Granted to a novel component that significantly enhances the performance of a display.

Gold and Silver awards are presented in each of the three categories

SID
2012
Society for Information Display
Awards
Display of the Year

Stereoscopic Display Technologies and Their Applications in Medical Imaging

The recent evolution of 3-D display technology will impact medical-imaging visualization. 3-D reconstruction systems and stereo cameras are widely available in medical modalities, and improved stereo 3-D visualization will enable new procedures and easier interaction with volumetric anatomy data. New image-quality metrics and basic requirements for stereo 3-D displays are therefore under development.

by Luigi Albani, Cédric Marchessoux, and Tom Kimpe

AS 3-D direct-view imaging systems are emerging in practically every display-related market (professional and consumer), it becomes increasingly important to have a method to qualify the displayed stereoscopic images. In the case of 2-D imaging systems, extensive work has already been done in the field of image and display qualification through the so-called human-visual-system (HVS) based metrics for image-quality assessment.[1-3] In the 3-D domain, however, such metrics have not yet been developed, although some preliminary results have already been published.[4-6] Nowadays, the majority of 3-D image-quality assessments still rely strongly on user tests[7,8,27,29,30] or applications,[28] whereas for medical applications, image quality is crucial. Since there is no full and reliable stereoscopic human-vision model, some metrics to assess the quality of stereoscopic images have already been proposed. These rely on the combination of a 2-D metric and a disparity map comparison[6] or on a simplified matching process between the left and right view to end up with a cyclopean view that is then qualified using a 2-D image-quality metric.[7] The use of a depth map to arrive at a cyclopean image (a mental image that contains information from the left and right view as well as depth information) can be helpful locally as well, as it enables features at different depth planes to be treated separately.[9]

For stereoscopic images, it is possible to use a 2-D image-quality metric to do an assessment of both the right- and left-view image and then combine the obtained metrics. This, however, does not take into account the depth information induced by the parallax between the two views. One could also define a metric for the disparity map and then combine it with the metrics for the left and right views to obtain one stereoscopic image metric. The approach proposed in this article combines the two views (left and right) and the depth information into one so-called cyclopean image using the data available in the disparity map [Fig. 1(a)]. This article will also investigate a proposed metric that can qualify 3-D medical images starting from a reference image. Several image-quality attributes that are crucial for medical applications, such as noise, blurring, contrast, or compression artifacts, can be estimated with this new methodology.

A Proposed Methodology

The stereoscopic image-qualification method could rely on the creation of a cyclopean image (normal view when looking at the scene) that could be scored with respect to a reference image using, for instance, the SSIM method used in 2-D image qualification.[10,11] This metric is limited to gray scale. Instead of using SSIM, the C4 metric described in Ref. 26 could also be used. The cyclopean image can be constructed from the left- and right-view image using the disparity map or the depth map associated with the stereoscopic image. The disparity map links pixels in the left- and right-view image that correspond with the same point in the stereoscopic image. In the approach proposed here, the disparity is defined as the horizontal displacement between corresponding pixels in the left- and right-view images with the position of the left-view image pixels as the reference position.

***Luigi Albani** is Technology Innovation Manager for BARCO Healthcare Division, FIMI S.r.l. Italy. He can be reached at. +39-02-96175 x348 or luigi.albani@barco.com. **Cédric Marchessoux** is Technology Innovation Project Manager for BARCO Healthcare Division, Belgium. He can be reached at +32-56-233-533 or cedric.marchessoux@barco.com. **Tom Kimpe** is responsible for worldwide research and innovation activities for BARCO's Healthcare Division. He can be reached at +32-56-233-385 or tom.kimpe@barco.com.*

0362-0972/10/2011-024$1.00 + .00 © SID 2011

The 3-D objects created for Fig. 1 are, for simplicity, a set of spheres. The different spheres are projected onto the screen for both views, and afterwards the results of the different spheres are added to yield the total left and right view of the scene. The proposed approach allows for reasonable computation time in comparison with more general matching methods. One or both of the views needs to be degraded or altered with respect to the reference image. A combination of blurring by convolution (a filter size of 11 or 21 pixels and a standard deviation: of six pixels) and lossy compression with JPEG (compression ratio from 10 to 75%) is examined in this article.

Employing the relative luminance values corresponding with both views using $L_c = [L_l^2 + L_r^2 + 2L_lL_r\cos(\theta)]^{1/2}$,[13] the cyclopean pixel can be calculated. Both summation and inhibition phenomena are taken into account depending on θ (the angle describing the amount of luminance summation occurring). The combination function ensures that Fechner's paradox is taken into account when luminance differences are present between the left and right views. Fechner's paradox corresponds to the fact that sometimes the brightness in binocular mode may be perceived to be not as bright as it is in monocular vision, due to luminance differences between the right and the left views. L is the luminance of the pixel (subscripts represent cyclopean left-view and right-view pixel, respectively). A $\theta = 120°$ is chosen because it corresponds to images with a large range of frequencies with a dominant inhibition factor. SSIM is an objective metric that can compare the structure of two images. The SSIM metric is applied on the reference and test cyclopean images to identify the differences between these images. The SSIM-based stereoscopic image-quality metric discussed above can be validated using a psycho-visual study with a set of images to be scored both by five observers in a normalized environment[14] as well as the SSIM-based method. The set consists of 40 stereoscopic images, of which 10 are used for the intra-observer variance com-

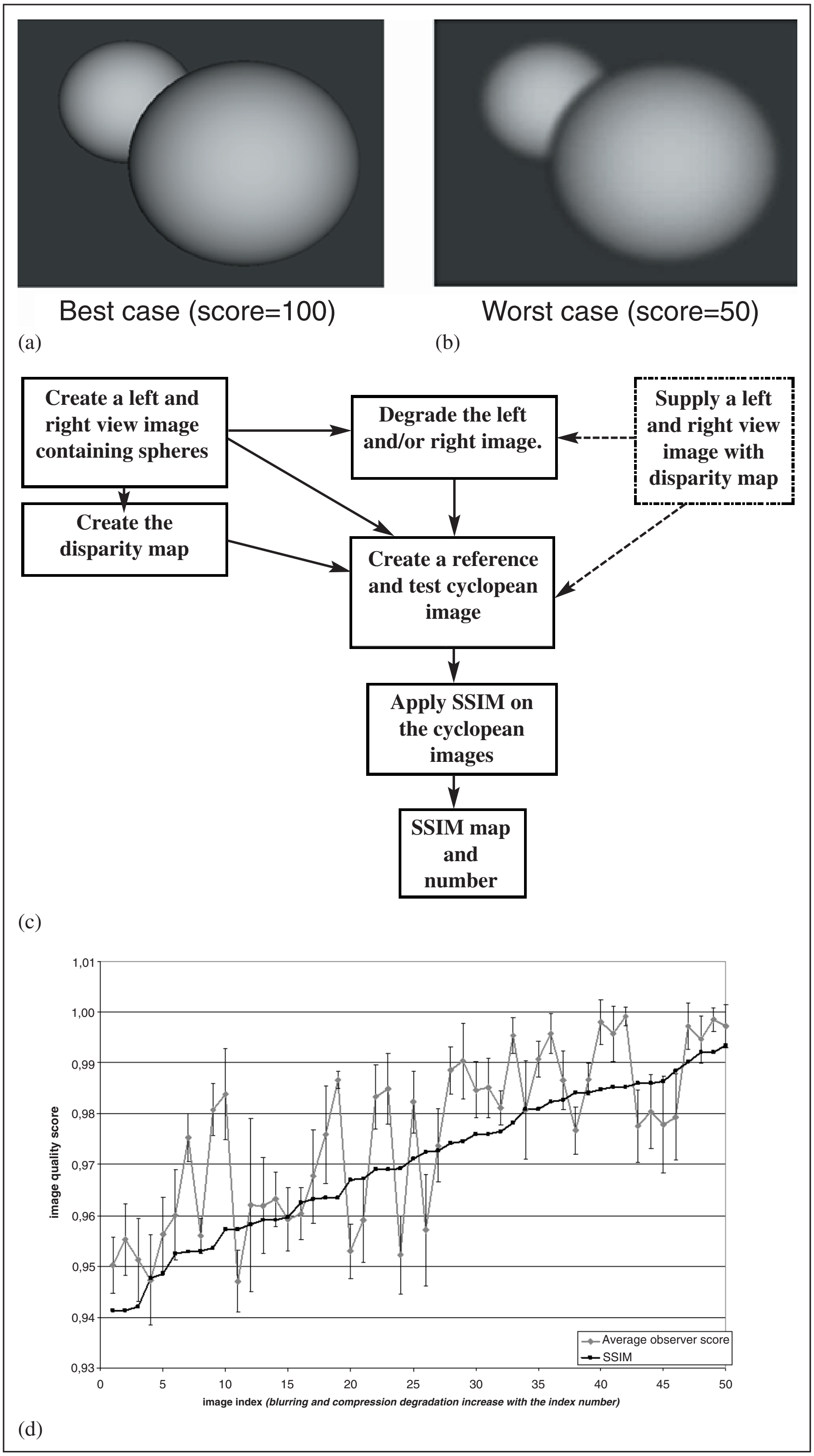


Fig. 1: (a) The spheres show the best image quality. (b) The spheres show the worst image quality. (c) The SSIM-based stereoscopic image-quality metric appears in schematic form. (d) The average observer score and the SSIM value are compared.

putation, resulting in 50 images to score for each observer. The observers are asked to score the test image relative to two reference anchor images (high and low quality).

As a preliminary result, Fig. 1(c) shows the average scaled observer score along with the associated error bars and the SSIM-based scores. So these results could be compared, the observer scores were scaled to the same region as the SSIM-based results. From the results shown in Fig. 1(d), it can be seen that generally a rather good correspondence exists between the SSIM-based metric and the observer test results. For the observer reproducibility, the scattering and the Kurtosis tests were used. The Kurtosis test, described in the norm ITU-R 500-10,[16] allows accepting or rejecting an observer by estimating the variation between one observer and the others, using the inter-observer variance. For the scattering, most of the observers have a low value. The averaged scattering for the five observers is equal to 2.3% with a minimum value of 1.9% and a maximum value of 2.6%. None of the observers is rejected by the Kurtosis test.

Applications in Medical Imaging

Recent studies indicate the benefits of stereoscopic imaging in diagnostic tasks such as early detection of breast cancer.[23-25] In standard 2-D mammography, "subtle lesions may be masked by the superimposition of overlying or underlying normal breast tissue and thus are undetectable"; on the contrary, "in a stereoscopic X-ray view of the breast, the subtle lesion is directly seen volumetrically, separated from overlying and underlying normal tissue in depth." [24] However, this technology has some limitations. The display is gray scale and the acquisition of the X-ray images needs to be adapted from the normal routine with two orientations – cranial caudal and medio-lateral oblique – to generate stereoscopic views per orientation. Also, the display itself is not so practical in terms of ergonomics (space, cleaning, *etc.*).

Nevertheless, clinical trials in Australia showed how – compared to standard digital mammography – the stereo methodology significantly reduced false-positive lesion detections by 46% and significantly increased true-positive lesion detections by 23%.[25]

In general, the benefits of 3-D imaging apply for nearly all types of medical images, and applications can range from surgery (neurosurgery, cardiac intervention, computer- or robot-assisted surgery, minimally invasive surgery, or surgical training) to intervention planning, radiotherapy, endoscopy, *etc.* Adoption of advanced 3-D visualization technologies directly impacts productivity, accuracy in the task, and safety. As an example, through 3-D vision a doctor can clearly distinguish if a blood vessel is in front of or behind another one and the doctor can immediately evaluate the depth of tumors.

Minimally invasive procedures have signaled a revolution in surgical intervention where remote operation and visualization techniques have been continuously improving to make these operations as natural as the traditional open-surgery procedures. One of the largest challenges in laparoscopic surgical training is the adaptation of a two-dimensional flat view of the surgical field. Stereo visualization can provide a more natural view as well as improved hand-eye coordination through augmented depth perception induced by binocular parallax and convergence depth cues.

In performance-oriented tasks, stereo 3-D displays – now becoming popular at a premium for entertainment and amusement purposes – will improve accuracy, reduce procedure time, and enable a shorter training period. The reason that the majority of the endoscope systems are now based on 2-D visualization is probably related to the limited quality of the 3-D displays available compared to the binocular eyepiece vision used in critical laparoscopic interventions with robot-assisted surgery.

Recent investments in 3-D technologies will enable the adoption of stereoscopic endoscopes with 3-D screens as soon as the latter demonstrate the appropriate level of image quality through a careful balance of brightness, resolution, crosstalk, and the sweet spot in the stereo visualization that is required to avoid visual discomfort.

3-D Display Solution and Motivation

In operating rooms, typically a full-HD 24-/26-in. display for personal viewing is used by the surgeon as well as for assistance or training purposes. Among the currently available technological options, the "passive-glasses solution" based on patterned-retarder displays has been selected as the most suitable one for minimally invasive surgical procedures. Autostereoscopic (glasses-free) displays currently have limited resolution and a fairly limited "sweet spot." Three-dimensional time-sequential displays based on active-shutter glasses are, most recently, reaching a performance level where they can be used by surgeons, but the ergonomics present challenges in operating-room environments. In comparison, 3-D polarized glasses are lighter, as well as more stable and reliable, and possibly disposable. This 3-D solution is based on a cross-polarized filter (quarter-wave retarder) that – combined with the linear-polarized light emitted by the LCD panel – displays alternated lines with opposite circular polarization (see Fig. 2).

Assessment and Performance

Crosstalk creates ghosting in the viewed images, which is considered a major cause of visual discomfort and becomes a critical factor in performance-oriented tasks.[18] Ghosting makes stereoscopic 3-D images hard to fuse, due to a loss of contrast and depth resolution. A definition of crosstalk as a physical entity that is objectively measurable is the system crosstalk (SCT), which describes the degree of light leakage through the unintended eye path generated by the display system under consideration.[17,19] A different metric is viewer crosstalk (VCT) or the crosstalk perceived by the viewer. This is defined as the ratio of the luminance of an unwanted ghost image, which leaks from the other eye image, to the correct luminance received by the viewer's eyes.[19] System crosstalk is independent of the content and characterizes the display, whereas VCT varies depending upon the content. The visibility of crosstalk is related to the binocular parallax in the co-located pixel and is proportional to the image contrast.[17] The amount of crosstalk considered acceptable or unacceptable is defined in the literature as follows: "crosstalk between 2 and 6% significantly affected image quality and visual comfort[20]; a crosstalk level of about 5% can induce visual discomfort in half of the population." [17] A crosstalk-visibility threshold of about 1% for natural content is recommended for professional 3-D displays.

For the sake of clarity, the crosstalk definition and its calculation are reported here in accordance with recent publication. It is under evaluation for new IEC and ICDM 3-D display-metrology standards.

The measurement of system crosstalk is performed by applying simultaneously a black-and-white two-view pattern, where the subscript left is referred to as "view 1" and

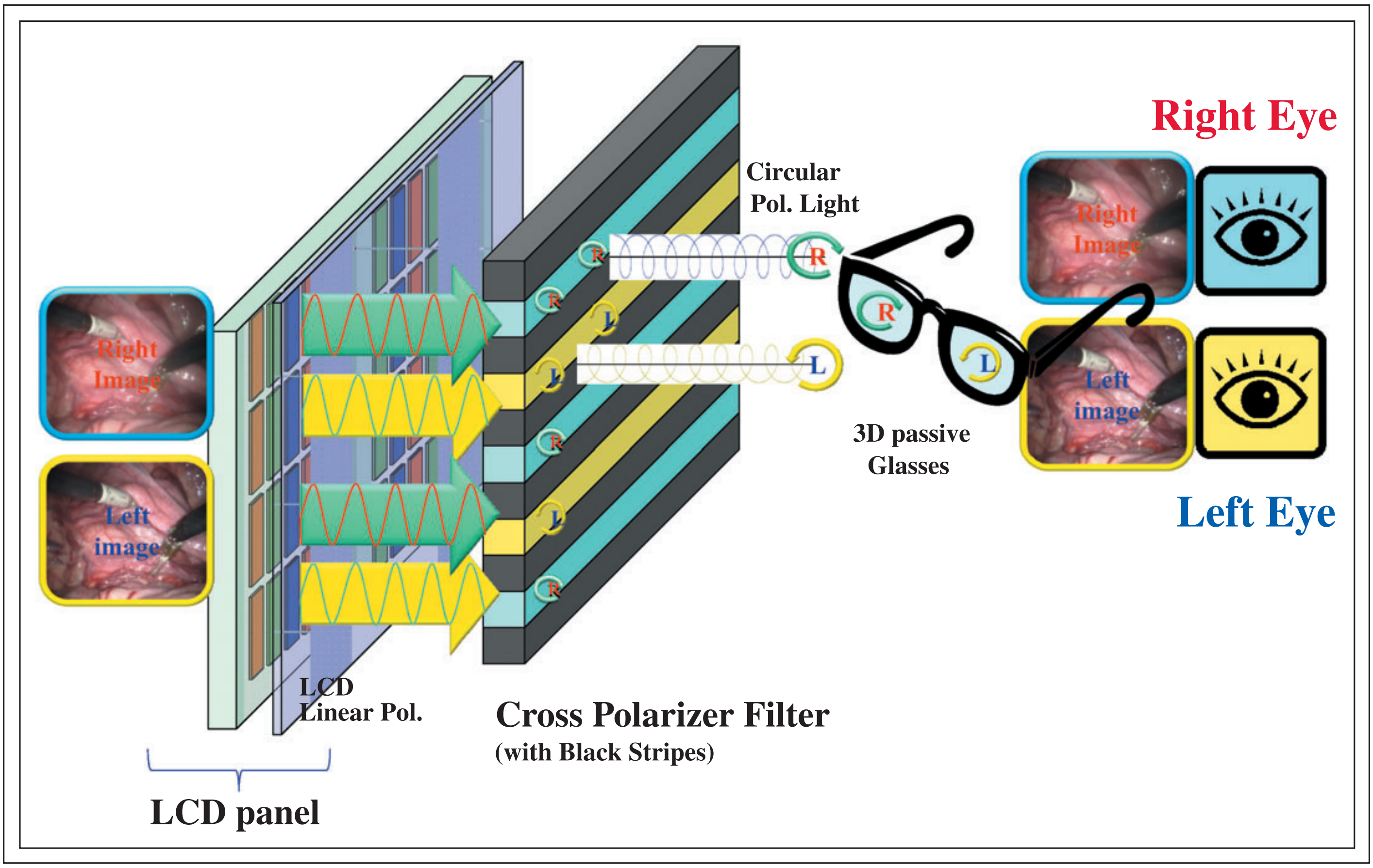


***Fig. 2**: This 3-D LCD construction is based on passive-glasses technology.*

right is referred to as "view 2," and where the "kw" subscript refers to the source image left = black and right = white. The center luminance is measured in the normal direction to the center of the display using a spectroradiometer after the matched left/right eye glasses.[19]

The SCT experienced by the left-eye and the right-eye views is calculated as follows:

$$\mathbf{SCT_L} = L_{1kw} - L_{1kk} / L_{1wk} - L_{1kk},$$
$$\mathbf{SCT_R} = L_{2wk} - L_{2kk} / L_{2kw} - L_{2kk},$$

where L_{iwk} is the view-i luminance measured with all white as left-eye source images and all-black as right-eye source images; L_{ikw} is the view-i luminance measured with all-black as left-eye source images and all-black as right-eye source images; L_{ikk} is the view-i luminance measured with all-black sources.

The level of SCT crosstalk on 3-D monitors with a pattern-retarder solution can drop below 1% with the appropriate selection of the key components in a stereo 3-D 24-in. medical display. The circular polarization induced in the emitted light is obtained by combining the linear-polarized light from the LCD panel and the quarter-wave retarder filter applied to its surface (Fig. 2). All the component materials from the LCD-panel technology (TN, VA, or IPS) and the process used to apply the filter play a relevant role in crosstalk minimization.[21] The polarizer lenses play a crucial role in the final crosstalk and need to be matched with the LCD panel as well as the cross polarizer adopted in the display. For instance, the polarization axes of the light emitted from a conventional LCD panel can range from polarization axes of 0°, 45°, 90°, or 135°. In the case of a wrong combination between the 3-D monitor and the 3-D glasses, the level of SCT can easily go above the visibility threshold and it could introduce colored ghost images of purple/reddish coloration, as shown in Fig. 3.

Current 3-D solutions with line-interleaved cross-polarizer filters have a limited viewing angle in the vertical direction due to their intrinsic construction (the LCD pixel matrix and the cross-polarizer filter are positioned on different planes). The vertical sweet spot is improved by adding black stripes on the cross-polarizer filter among the display lines, but may result in brightness reduction and a more critical need for alignment (an error can introduce moiré visible when in 2-D mode). Viewers can move freely in the horizontal direction without losing the correct stereo viewing, while in the vertical direction a 3-D viewing angle of ±10° (3-D vertical sweet spot) is reached starting with a conventional 24-in. LCD panel.[21] A specific design for a 3-D LCD panel will achieve a wider 3-D vertical viewing angle by reducing the thickness of the LCD front glass and utilizing new LCD cell structures with an embedded quarter-wave retarder and polarizer.

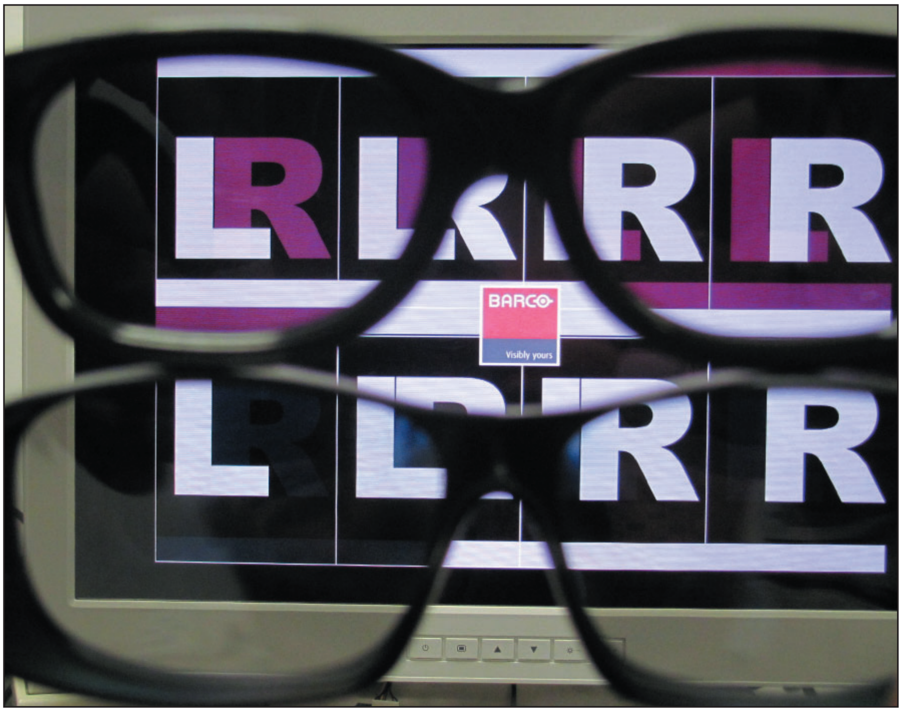


***Fig. 3**: Through the glasses at the top, a mismatch between the 3-D circular-polarizer glasses and a 3-D LCD monitor can be seen, and through the pair at the bottom, a correct combination can be seen.*

Theoretically, the vertical resolution of single left- or right-eye views is reduced, but, practically, the loss of resolution is not significantly noticeable. In fact, when a video signal is delivered in interlace format, the signal information present is intrinsically limited in the vertical direction (the Kell effect). Otherwise, full Nyquist high-frequency content can lead to visible line flickering or aliasing (as shown in (Fig. 4); after a de-interlacing process[22] for display on progressive LCD screens.

Future Medical Applications

In terms of future applications, stereoscopic displays combined with 3-D echocardiography have been shown to improve the visualization of real-time ultrasound images, decreasing the time required for surgical task completion and increasing the precision of instrument navigation. Another potential application is the visualization of 3-D artery trees from angiography, MRI, or CT acquisitions. 3-D visualization in the coronary tree of the heart would have some benefit before an angioplasty because it would help to correctly estimate the degree of the stenosis. Other possible applications of new 3-D displays include use in anatomy teaching, treatment planning, stereo mammography, and for recent new modalities such as digital breast tomosynthesis.

In terms of the nearer future, there are several medical-imaging applications for which information is already available in the three-dimensional space: computer tomography, magnetic resonance, multi-projection X-ray, 3-D ultrasound, binocular microscopes, *etc.* Volumetric 3-D rendering is currently being employed on high-quality 2-D displays; this application could benefit from the new stereo 3-D display technology.

Challenges and Opportunities

Such technology will be introduced only after the required validation steps for diagnostic usage have been taken. A new quality metric must be defined and an example proposed. The assessment of image quality with respect to perception is still under development and no standards or well-accepted methods yet exist.

The potential is great; however, in applications involving the manipulation of a medical device during an image-guided interventional procedure, real-time stereo 3-D perception improves hand-eye coordination and enhances the comprehension of complex anatomical structures. For this reason, 3-D display technology is likely to find its next applications in procedures such as laparoscopy; neuro, spine, and ophthalmic surgery and cardiovascular procedures. Selection among the available 3-D technologies should aim first at minimizing visual fatigue and discomfort, taking into consideration the critical and continuous nature of the visualization tasks and at the same time providing the best image quality without artifacts. It is foreseen that the specificity of all the different medical tasks will lead not to one solution for stereo 3-D displays but to a number of displays tailored to meet particular objectives, as occurred with the range of 2-D medical displays currently in use.

References

[1] P. G. J. Barten, *Contrast sensitivity of the human eye and its effects on image quality* (SPIE Optical Engineering Press, 1999).

[2] S. Daly, “The visible differences predictor: an algorithm for the assessment of image fidelity,” *Digital images and human vision* (MIT Press, Cambridge, 1993), pp. 179–205.

[3] J. Lubin, “A visual discrimination mode for image system design and evaluation” (E. Peli, ed.), *Visual Models for Target Detection and Recognition* (Singapore World Scientific, 1995), pp. 207–220.

[4] A. Benoit, P. le Callet, P. Campisi, and R. Cousseau, “Quality assessment of stereoscopic images,” *JIVP* **659204**, 1–13 (2008).

[5] P. Gorley and N. Holliman, “Stereoscopic image quality metrics and compression,” *Proceedings of SPIE Stereoscopic Displays and Applications XIX* **6803**(1), 680305.1–680305, 12 (2008).

[6] A. Boev, A. Gotchev, K. Egiazarian, A. Aksay, and G.B. Akar, “Towards compound stereo-video quality metric: a specific encoder-based framework,” *Proceedings of IEEE Southwest Symposium on Image Analysis and Interpretation*, 218-222 (2006).

[7] R. Patterson, A.S. Boydstun, J.A Rogers, and L.M. Tripp, “Stereoscopic depth perception and interocular luminance differences,” *SID Symposium Digest* **40**(1), 815–818 (2009).

[8] P. J. H. Seuntiens, L. M. J. Meesters, and W. A IJsselsteijn, ”Perceived quality of com-

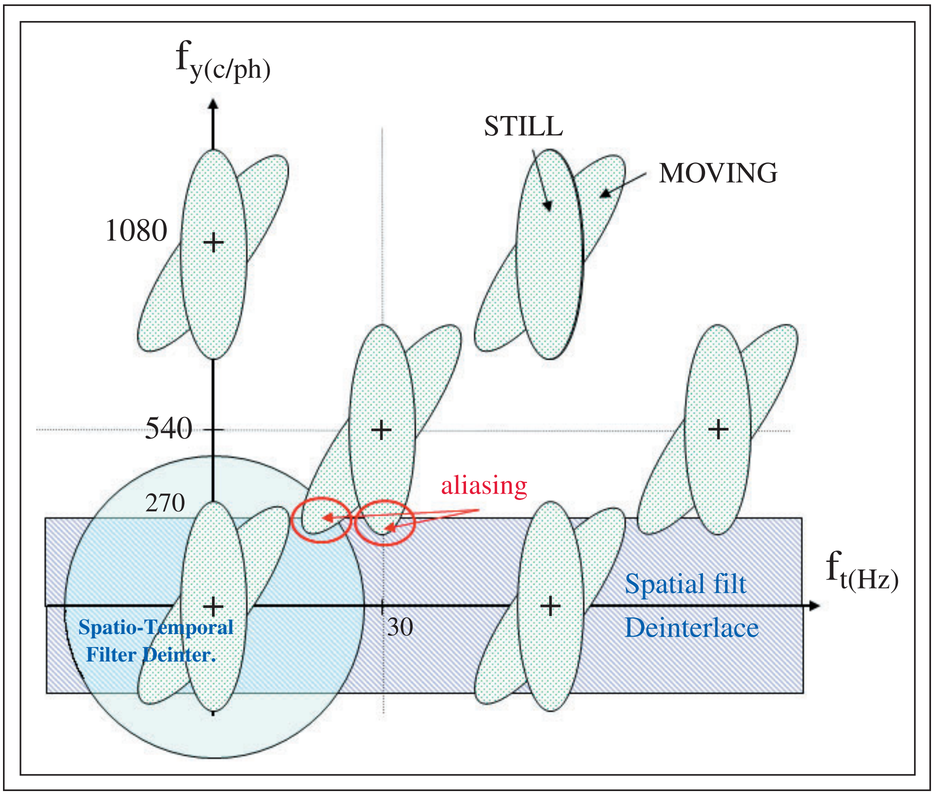


Fig. 4: *Shown is the frequency spectrum of interlaced video signals.*

pressed stereoscopic images: Effects of symmetric and asymmetric jpeg coding and camera separation," *Journal ACM Transactions on Applied Perception* **3**(2), 95–109 (2006).

[9] W. D'Oosterlinck and C. Marchessoux, "New methodology for evaluating quality of stereoscopic images," *SID Symposium Digest* **41**, 522-525 (2010).

[10] Z. Wang, E. P. Simoncelli, and A. C. Bovik, "Multi-scale structural similarity for image quality assessment," *Proc. IEEE* ACSSC **2**, 1398–1402 (2003).

[11] Z. Wang, A. C. Bovik, H. R. Sheikh, and E. P. Simoncelli, "Image quality assessment: From error visibility to structural similarity," *IEEE Transactions on Image Processing* **4**(13), 143–152 (2004).

[13] I. P. Howard and B. J. Rogers, *Binocular Vision and Stereopsis* (Oxford University Press, Oxford Psychology Series, 1995).

[14] C. Marchessoux and T. Kimpe, "Specificities of a psychophysical test room dedicated for medical display applications," *SID Symposium Digest* **38**, 971-974 (2007).

[16] ITU-R, Recommendation BT.500-10, "methodology for the subjective assessment of the quality of television pictures," Tech. Rept., ITU, Geneva (2002).

[17] A. Woods, "Understanding Crosstalk in Stereoscopic Displays," (Keynote presentation), 3DSA, Tokyo, Japan (2010).

[18] K. C. Huang, J. C. Yuan, C. H. Tsai, W. J. Hsueh, and N. Y. Wang, "A study of how crosstalk affects stereopsis in stereoscopic displays," *Proceedings of SPIE Stereoscopic Displays and Virtual Reality Systems X* **5006**, 247–253 (2003).

[19] K. C. Huang, K. Lee, and H. Y. Lin, "Crosstalk issue in Stereo/Autostereoscopic Display," *Proc. IDMC*, 2–18 (2009).

[20] L. Chen, Y. Tu, W. Liu, Q. F. Li, K. Teunissen, and I. Heynderickx, "Investigation of Crosstalk in a 2-View 3-D Display," *SID Symposium Digest* **39**, 1138–1141 (2008).

[21] Y. Yoshihara, H. Ujike, and T. Tanabe, "3-D Cross talk of stereoscopic (3-D) display using patterned retarder and corresponding glasses," *Proc. IDW '08*, 1135–1138 (2008).

[22] G. de Haan and E.B. Bellers, "Deinterlacing – An overview," *Proc. IEEE* **86**, No. 9, 1839–1857.(1998).

[23] D. J. Getty, "Stereoscopic Digital Mammography," *Proceedings of 1st Americas Display Engineering and Applications Conference*, 11–14 (2004).

[24] D. J. Getty, C. J. D'Orsi, R. M. Pickett, M. S. Newell, K. R. Gundry, S. F. Roberson, and S. R. Bates, " Stereo mammography takes breast imaging to a new dimension," RSNA (2007).

[25] D. J. Getty, "An evaluation of stereoscopic digital mammography for earlier detection of breast cancer and reduced rate of recall," Clinical Trial Austalia – Novotech, The Australian CRO (2008).

[26] M. Carnec, P. Le Callet, and D. Barba, "An image quality assessment method based on perception of structural information," *Proceedings of IEEE Intl. Conf. on Image Processing* (2003).

[27] J. Hakkinen, T. Kawai, J. Takatalo, T. Leisti, J. Radun, A. Hirsaho, and G. Nymana, "Measuring stereoscopic image-quality experience with interpretation based quality methodology," *Proc. SPIE IS&T Electronic Imaging*, 6808 (2008).

[28] J. Seo, D. Kim, and K. Sohn, "Compressed Stereoscopic Video Quality Metric," *Proceedings of SPIE IS&T Electronic Imaging* 7237, 12-1– 12-11 (2009).

[29] A. Kuijsters, W. A. IJsselsteijn, M. T. M. Lambooij, and I. E. J. Heynderickx, "Influence of chroma variations on naturalness and image quality of stereoscopic images," *Proceedings of SPIE IS&T Electronic Imaging* **7240**, 0E-1 – 0E-9 (2009).

[30] L. Goldmann, F. De Simone, and T. Ebrahimi, "A comprehensive database and subjective evaluation methodology for quality of experience in stereoscopic video," *Proceedings of SPIE IS&T Electronic Imaging* **7526**, 0S-1 – 0S-11 (2010). ■

From Our European Chapter: New Facility in Germany Will Enable Next-Generation OLED Materials

In a definitive show of support for an up-and-coming technology, Merck KGaA has invested approximately 50 million Euros in a new flagship research complex dedicated to developing new products and applications, including organic light-emitting diodes (OLEDs) and liquid-crystal mixtures. The Material Research Center (MRC) includes three laboratory and pilot-plant buildings at the company's site in Darmstadt, Germany (Fig. 1).

This facility represents the largest single investment to date in chemicals research and development at Merck. According to the company, approximately 340 employees are currently developing new products and applications at the Material Research Center. Such products include the aforementioned OLEDs and liquid-crystal mixtures, as well as highly efficient energy storage systems, biochemical as well as microbiological analyses, and additional innovative materials. Merck believes that locating researchers together in the new MRC not only stimulates discussions and the exchange of ideas, but also promotes synergies among various research topics and among the different materials developers, physicists, application engineers, and analytical scientists.

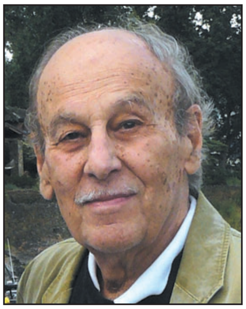
Fig. 1: Merck's new flagship chemical research complex in Darmstadt, Germany, comprises 11,000 square meters of workspace. Photo: Merck KGaA, Darmstadt, Germany

OLED materials are one of the focus areas within the MRC, and OLED experts are currently conducting research on innovative products and applications and developing high-performance materials for solution-processed as well as evaporated OLEDs. Researchers in chemical synthesis, material screening, and the application lab, which is designed for building state-of-the-art OLED test cells, are working hand-in-hand to constantly improve material performance and find customized solutions for different display and lighting applications.

The foyer of the MRC is outfitted with the world's largest OLED display, which is being used for presentations and events (Fig. 2). The display was produced by Mitsubishi Electric Corp. It has a surface area of almost 9 square meters and weighs approximately 480 kilograms. According to Merck, this is the first time that OLED technology has been successfully deployed in such a large-format display, although LEDs (light-emitting diodes) have long been used for large displays in venues such as sport stadiums, train stations, and airports. ■

Fig. 2: The world's largest OLED display (nearly 9 square meters) is located in the new Material Research Center at Merck in Darmstadt. Photo: Merck KGaA, Darmstadt, Germany

In Memoriam: Thomas Peter Brody, SID Fellow and Display Pioneer, Dies at 91



"The cathode-ray tube, like the brontosaurus, will become extinct, and for the same reason: too much bulk, very little brain." – *T. P. Brody, 1981*

Dr. Thomas Peter Brody, a Fellow of the Society for Information Display and a recipient of numerous awards in recognition of his pioneering work, has died at age 91. During his lifetime, Brody published over 70 scientific papers and received more than 60 patents. Among the many awards he received were a SID Special Recognition Award, a SID Fellowship, the SID Karl Ferdinand Braun Prize, the Rank Prize in Optoelectronics (UK), the Eduard Rhein Prize (Germany), and, most recently, the IEEE Jun-Ichi Nishizawa Medal.

Brody was born in Budapest, Hungary, in 1920. In 1938 he left home to train as a master printer at the London College of Printing, intending to take over the family business. Brody also studied piano at the Guildhall School of Music in London and, as a concert pianist, gave recitals in venues including St Martin-in-the-Fields.

He served in the British Army during and after the Second World War, working as a designer/draftsman and in the Special Operations Unit. After being demobilized with the rank of staff captain, Brody met his future wife Maude at a Fabian Society dance in London. They married in 1952.

Brody received his Ph.D. in theoretical physics in 1953 from the University of London. From 1953 to 1959, he worked as Senior Lecturer in Physics at the University. He was offered the opportunity to work for the Research Laboratories of Westinghouse Electric Corporation in 1959 and moved with his wife and young daughter to Pittsburgh, PA, that year.

From 1959 to 1979, he did theoretical work on tunnel diodes, semiconductor device theory and experiment, injection luminescence, field emission, and pattern recognition. He eventually turned his interest to thin-film technology.

Over the years 1968–1979, Brody developed many electronic uses for thin-film transistors, including flexible circuits, aircraft power controls, and industrial timers. His work at Westinghouse culminated in the invention and full development of active-matrix flat-panel-display technology. His department built the world's first active-matrix liquid-crystal displays (AMLCDs) in 1972, the first AMEL displays in 1973, and demonstrated real-time video imagery on both types in 1974. He coined the term "active matrix" and introduced it into the literature in 1975.

When Westinghouse cancelled the research program in 1979, Dr. Brody resigned, and two years later founded Panelvision Corporation, the world's first AMLCD company. In 1983, the company introduced the first AMLCD products into the U.S. market. Panelvision was acquired by Litton Systems in 1985, and after a period of consulting, Brody founded Magnascreen Corporation, oriented towards very-large-area displays, in 1988.

Brody left Magnascreen in 1990 to form Active Matrix Associates, a consulting group, and over the period 1991–1997 worked on a number of classified projects for the Defense Advanced Research Projects Agency (DARPA). In 1998, in collaboration with two former Westinghouse colleagues, he invented a process for fabricating low-cost thin-film electronic circuits by purely additive processes. In 2002, he founded Amedeo Corporation (now Advantech US), dedicated to the exploitation of additive technology. The company is concentrating on the development and eventual commercial production of low-cost active-matrix backplanes for emerging display technologies. He was active as Chief Scientist of Advantech US until his death.

Brody was a devoted husband to his beloved wife Maude for 58 years and a loving father to his four children Louise, Francine, Christopher, and Sarah. Throughout his distinguished career, family remained a focal point of his life. He is survived by his younger brother Ferenc, his children, and four grandchildren.

A memorial service was held in Pittsburgh in September. For further information on Brody's life and work, contact Louise Brody at (412) 362-4471 or email louise@lcstudio.net. ■

continued from page 2

At the same time, our team at *ID* is still committed to making the hardcopy business model survive. (I don't think anything can replace the experience of holding and reading a printed magazine.) This month begins the first of at least a couple issues per year that will be published on a regular monthly cycle but printed and distributed only in pairs. Beginning next month, we'll combine the November and December issues into one similar to our current approach for May/June, and July/August. We sincerely hope our readers will appreciate and understand these steps as necessary. As SID members, we all need to find creative ways to adapt with the times.

If you are someone involved in the business development side of your company and you do not currently advertise in *ID*, we sincerely hope you will take another look and give us a chance to help your business. *ID* is the exclusive source for the most thorough and completely balanced technology information to the display industry and beyond. Our team of guest editors and industry experts ensures that everything we publish is based on a sound technical foundation designed to educate and inform our readers, most of whom work in the same industry. Engineers and product developers can do their jobs better every day because of the information we deliver. If your company provides a product or service to the industry, it's likely we have covered your work or have published an article written by someone on your technical staff. Think about helping us and increasing awareness for your own business at the same time by advertising with *Information Display*.

We begin our lineup this month with a Frontline Technology feature entitled "Clearing the Road to Mass Production of OLED Television" by David K. Flattery *et al.* from Dupont Displays. Even though the promise of mass-produced low-cost OLED TVs has been a bit longer than originally expected in coming to reality, in the background, there have been significant advances in materials, manufacturing processes, and material utilization efficiencies, as well as brighter prospects for large-area yields and production rates. David and his team discuss some of the most important aspects of those improvements and you will find their analysis very encouraging.

Meanwhile, analyst Paul Semenza provides us with a similarly optimistic view for the future of mass production of OLED displays in his Display Marketplace feature "OLEDs in Transition." We challenged Paul to tell us why this time it's different, and he delivered with an expert survey of both the market demands by key applications and the landscape of investments by key producers. The geography is certainly converging and the investment dollars are lining up as well, with new factories coming on line and raw capacity approaching 9 million square meters per quarter in 2014. While those are not yet as impressive as LCD capacities, they represent enough output to overcome the limited economy-of-scale issue we're seeing today and certainly to solidify the process parameters and economic models that will drive a maturing production landscape.

Continuing on our OLED theme, authors Yu-Cheng Chen, Ulrich Hausmann, and David Knowles discuss the latest advances in laser-crystallization technology to produce cost-efficient polysilicon TFT backplanes on very large substrates. In their article entitled "Beyond Amorphous Silicon: New Developments in High Mobility Backplanes," the authors discuss their innovations in both laser power densities and coverage areas, which reduce cycle time and decrease production cost for large substrates, even up to Gen 8. In a very real sense, this is where the money is in OLED technology – building the manufacturing-process infrastructure to make the jump to large-scale manufacturing of substrates and whole displays.

Our second Frontline Technology feature for this month is a detailed discussion on "Stereoscopic Display Technologies and Their Applications in Medical Imaging" by Luigi Albani, Cédric Marchessoux, and Tom Kimpe of Barco Corp. This topic is very interesting to me because I have heard many lectures on the subject of using stereoscopic display technology to enhance the value of electronic radiology and MRI images, and maybe even real-time surgical procedures. Several of *ID*'s past contributors have written about this topic and some have developed early concept products with limited success. Stereoscopic medical imaging is of perennial interest at Display Week and it comes up frequently in Boston display-community gatherings. However, there is always that element of concern about the human factor and whether the stereoscopic effect is more beneficial or detrimental to the intended result. No one has treated the subject in a more comprehensive and thoroughly understandable common sense way than our friends who have written this most recent article. I think you will find this an extraordinarily complete treatment of this subject and I'm glad we could finally bring it to you as part of this issue.

Finally, on a somber note, we lost a well-known colleague and display-industry pioneer on September 18, 2011. Dr. Peter Brody is widely recognized as an industry pioneer who developed the active-matrix backplane for LCDs as well as many other applications. He published over 70 scientific papers and received more than 60 patents – his work lives on today in endless display applications. I'm told he never missed a single Display Week conference. He will be missed by many. ■

Journal of the SOCIETY FOR INFORMATION DISPLAY

SID
SOCIETY FOR INFORMATION DISPLAY

The following papers appear in the October 2011 (Vol. 19/10) issue of *JSID*.
For a preview of the papers go to sid.org/jsid.html.

Special Section on Vehicle Displays

Vehicle Displays

658–664 ***Review Paper:*** **The Helmholtz-Kohlrausch effect**
Robert L. Donofrio, Display Device Consultants, USA

665–670 **Optimization suggestions for instrument-cluster information using displays**
Arthur S. Brown, Vyacheslav Birman, and Eric Miciuda, Continental Automotive Systems, USA

Contributed Papers

3-D Displays and Systems

671–674 **Image correction based on homography in stereoscopic projection display**
Jun Liu, Qiong-Hua Wang, Xiao-Qing Xu, and Jun Gu, Sichuan University, China

675–678 **Two-parallax-barriers-based autostereoscopic liquid-crystal display without cross-talk**
Jiang-Yong Luo, Qiong-Hua Wang, Wu-Xiang Zhao, Lin Qi, and Guo-Kai Shi, Sichuan University, China

679–684 **An integral-imaging three-dimensional display with wide viewing angle**
Huan Deng, Qiong-Hua Wang, Lei Li, and Da-Hai Li, Sichuan University, China

Display Metrology

685–692 **Character-contrast measurements on reflective displays using replica masks**
Edward F. Kelley, KELTEK LLC, USA; Caesar Eghtesadi, Tech For All, Inc., USA;
Morgan Blubaugh and William Reuschel, The American Foundation for the Blind, USA

Electronic Paper

693–699 **Shrunk multiline addressing method in a passive-matrix-driven liquid powder display**
Michihiro Asakawa, Sadayuki Kaneko, and Reiji Hattori, Kyushu University, Japan

Interactive Displays

700–705 **The effects of topology and task complexity on digital-speech-desktop interface design and evaluation**
Wen-Te Chang and Ming Chuan University, Taiwan, ROC; Chien-Hsiung Chen, National Taiwan University of Science and Technology, Taiwan, ROC

Display Week 2012

June 3–8, 2012
Boston Convention & Exhibition Center
Boston, Massachusetts, USA

History in the Making

SID
DISPLAY WEEK
Boston 2012

Boston is a city with a rich history of innovation and progress. It serves as the perfect host for the 2012 SID International Symposium, Seminar & Exhibition. Display Week will be held June 3–8 at the Boston Convention & Exhibition Center. The exhibition will be open from June 5 to 7.

Display Week is the once-a-year, can't-miss event for the electronic-information-display industry. The exhibition is the premier showcase for global information-display companies and researchers to unveil cutting-edge developments in display technology. More display innovations are introduced year after year at Display Week than at any other display event in the world. Display Week is where the world got its first look at technologies that have shaped the display industry into what it is today; that is, liquid-crystal-display (LCD) technology, plasma-display-panel (PDP) technology, organic light-emitting-diode (OLED) technology, and high-definition TV, just to name a few. Display Week is also where emerging industry trends such as 3-D, touch and interactivity, flexible and e-paper displays, solid-state lighting, digital signage, and plastic electronics are brought to the forefront of the display industry. First looks such as these are why over 6500 attendees will flock to Boston for Display Week 2012.

sustaining members

Advantech US, Inc.
Applied Concepts, Inc.
Astra Products, Inc.
AU Optronics Corp.
autronic–Melchers GmbH

CDT, Ltd.
Chi Mei Optoelectronics Corp.
Corning Incorporated
Cyantek Corp.

Dawar Technologies, Inc.
Dontech, Inc.

eMagin Corp.
Epoxy Technology
Eternal Chemical Co., Ltd.
EuropTec USA, Inc.

Hanwang Technology Co., Ltd.
Henkel (China) Investment Co., Ltd.
Hitachi, Ltd.

IGNIS Innovation, Inc.
Industrial Electronic Engineers, Inc. (IEE)
Instrument Systems GmbH

Kuraray Co., Ltd.

LXD, Inc.

Mitsubishi Chemical Corp.
Mitsubishi Electric Corp.

Nano-Proprietary, Inc.
NANOSYS
NEC Corp.
NextWindow
Nippon Seiki Co., Ltd.
Noritake Itron Corp.
Novaled AG

Ocular
Optical Filters, Ltd.

Panasonic
Parker Chomerics/Silver Cloud
Photo Research, Inc.
Planar Systems, Inc.

Quantum Data, Inc.

Radiant Imaging, Inc.
Reflexite Display Optics
ROLIC Technologies, Ltd.

Sartomer USA LLC
Sharp Corp.
SLENCIL Co.

Tannas Electronics
Tatsuta Electric Wire & Cable Co., Ltd.
TE Touch Solutions/Elo TouchSystems
Teijin DuPont Films Japan, Ltd.
TFD, Inc.
TLC International
Trillion Science, Inc.

Universal Display Corp.
US Micro Products

Vestal Electronics A.S.

Westar Display Technologies, Inc.

index to advertisers

Business and Editorial Offices

Palisades Convention Management
411 Lafayette Street, Suite 201
New York, NY 10003
Jenny Donelan, Managing Editor
212/460-9700
fax: 212/460-5460
jdonelan@pcm411.com

Sales Office – Asia

Dr. Jia-Ming Liu
Industrial Technology Research Institute
Building 77 Chungsing Road, Sec. 4
Chutung, Hsinchu 310 Taiwan
+886-3-591-6939
fax: +886-3-582-0217
jiamingliu@itri.org.tw

Sales Office – Europe

George Isaacs
12 Park View Court
The Paddock, Eaton Ford
St. Neots, Cambridgeshire
PE19 7SD U.K.
+44-(0)-1480-218400
george@gandg.demon.co.uk

Sales Office – Taiwan

Jie Tsai, Project Manager
ACE Forum, Inc.
10F-1, No. 180, Sec. 4
Nanjing E. Rd.
Taipei 105, Taiwan
+886-2-2570-6960 x302
fax: +886-2-2570-2305
jie@aceforum.com.tw

Sales Office – U.S.A.

Christine von Steiger, Sales Manager
Palisades Convention Management
411 Lafayette Street, Suite 201
New York, NY 10003
413/783-0473
fax: 413/783-0474
cvonsteiger@pcm411.com

Michele Klein, Sales Coordinator
Palisades Convention Management
411 Lafayette Street, Suite 201
New York, NY 10003
212/460-8090 x216
fax: 212/460-5460
mklein@pcm411.com


LOCTITE®
A bright future.
Cover Lens
Plastic / Glass
LOCA
ITO
Plastic / Glass
LOCA
ITO
Plastic / Glass
LOCA
LCD Module