DISPLAY MANUFACTURING ISSUE

Information DISPLAY

SID
SOCIETY FOR INFORMATION DISPLAY

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

December 2009
Vol. 25, No. 12

Creating New Technologies through Mainstream Manufacturing

OPTICAL WAVEGUIDES FABRICATED WITH FLEXIBLE-SUBSTRATE-BASED MANUFACTURING TECHNIQUES

FLEXIBLE eBOOK DISPLAYS MADE WITH GLASS-DISPLAY MANUFACTURING EQUIPMENT AND PROCESSES

TFT-LCD MANUFACTURING CONTINUES TO EVOLVE

HOW POLYSILICON STACKS UP AGAINST AMORPHOUS SILICON

Plus
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Notebooks with Vikuiti™ Films Require Fewer Charges.

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COVER: Samsung LCD's Tanjeong complex in South Korea includes three Gen 8 lines that over the past few years have added 200,000 substrates (measuring 2200 × 2500 mm) to Samsung LCD's overall monthly production capacity. The Gen 8 LCD lines primarily produce LCD panels for 52-in.-diagonal or larger TVs. The sprawling Samsung LCD complex (2 million square meters) also includes two Gen 7 lines. One, a joint venture with Sony Corp., mainly produces 40- and 46-in. TV panels, and the other, a line exclusive to Samsung, produces panels from 32 to 82 in.

CREDIT: Samsung Tanjeong LCD Production Complex
Cover design by Acapella Studios, Inc.

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Information Display

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INFORMATION DISPLAY (ISSN 0362-0972) is published eleven times a year for the Society for Information Display by Palisades Convention Management, 411 Lafayette Street, 2nd Floor, New York, NY 10003; Leonard H. 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 Easton, PA.

Information DISPLAY

DECEMBER 2009
VOL. 25, NO. 12

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

editorial

Lessons from the Year That Was . . .

by Stephen P. Atwood

Every time I sit down to write the December editorial, I get a chance to consider the events of the previous year as well as look ahead to the coming year. For many of us, this past year brought challenges both economic and professional that we would rather not dwell on too long. For some, the sentiment may even be along the lines of "Good Riddance." However, before we say goodbye to 2009 we should at least be willing to acknowledge that sometimes adversity and hardship serve a positive role.

One example can be seen in the triumphs of many display businesses that have continued to innovate and grow their technology portfolios despite the downturn. While facing economic hardship, some companies made smart staffing and expense decisions, accepting the challenge to streamline their operations while not stifling their technology developments. These companies have now emerged with an even better business than they had before. You can spot them as the ones that continue to exhibit new products, influence the industry trends, lower the costs for adaptation of display technology, and set up world-class manufacturing facilities like the one pictured on the cover of this month's issue. Not all the winners are large; some are just small engineering or consulting firms, but they do typically have some key things in common, such as strong cash positions, good technology portfolios, a lean and aggressively motivated workforce, and senior leadership that is not afraid of failure but rather embraces challenge.

There is a contrasting trend I have seen illustrated by many companies when in the midst of an economic downturn. It starts by hunkering down as though they were under siege. They cut expenses, including staff, put technology developments on hold, and struggle to break even while minimizing loss of market share. Sometimes they have no choice because they lack enough cash or face crippling debt. These companies rarely survive a recession anyway. In few cases do those companies emerge from the crisis better positioned to succeed. However, there is another group that does essentially the opposite. They re-structure to minimize the cost of the less productive parts of their business while turning their remaining resources squarely to the goals of technology development and product innovation. They use the downturn as a chance to re-focus their energy and get ahead of the curve while their competitors are standing still. When the crisis is over, it is obvious they will emerge with better market share and less competition at the same time. It is these companies and their leaders that I admire most.

Consider the acquisition of E Ink by Prime View International. This deal was put together in May, just as the hardest period of the recession was looming. Although the eBook field was a hot topic around the water cooler, real sales were not record setting, and many product competitors were entering the space at the same time. A lot of deals were being scuttled and there was much handwringing about the lack of capital and optimism in the M&A world. However, both parties could see that a shakeout would only last a short time and the strongest product developers would emerge. Most of the new products being launched were based on some element of the E Ink system, and Prime View wanted to be positioned to be the supplier of choice for those and many more developers in the future.

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Information
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Green Manufacturing: End-of-Life Issues Are Complex

by Jenny Donelan

From California's Electronic Waste Recycling Act to the European Union's Waste Electrical and Electronic Equipment Act (WEEE), the government mandates continue to mount: electronics manufacturers must take steps to ensure their products, at end of life, are collected and recycled. California's legislation calls for a waste-recycling fee at point of sale (end users pay this), and for distribution of payments to waste recycling and collection agencies. WEEE sets targets for collecting and recycling equipment, with the responsibility for making this happen lying mostly with the manufacturer.

"Responsibility" is a big part of the recycling equation. Who is responsible for which actions and can they be made accountable? Due to the complexity of today's supply chains, answers to these questions can be hard to find. When it comes to recycling electronics, getting from mandate to "mission accomplished" is a difficult path for nearly all the parties involved. But one thing is certain: the success or failure of any given recycling initiative resides mostly with consumers. Their buy-in is vital in order for a plan to thrive.

Where Used Electronics End Up

There's no doubt that measures are necessary. According to a recent report from the U.S. Environmental Protection Agency (http://www.epa.gov/waste/conserve/materials/ecycling/manage.htm), approximately 235 million unused electronic devices had accumulated in storage in U.S. homes and offices as of 2007. Not all of these contain displays, but most do: this figure includes 43 million computer monitors, 2 million notebooks, and 99 million televisions.

Of those items that do make it out of the closet or the desk drawer and into the waste stream, very few are recycled. According to the same EPA report, between 2006 and 2007, out of 2.25 million tons of TVs, cell phones, and computer products at end of life, 18% were collected for recycling and 82% were disposed of primarily in landfills, where they are liable to leach hazardous chemicals into the ground and water supply. Although display manufacturers and others have been working hard of late to remove toxic materials from their products, the great majority of outdated or broken cell phones and other electronics residing in storage predate these efforts and so represent a considerable environmental hazard. And as electronic products continue to evolve in terms of features, stimulating consumers' desire to replace old models with new ones, the backlog of outdated products will only increase. According to the Consumer Electronics Association, U.S. consumers bought 2.9 million HD TVs for Super Bowl 2009 alone.

Recycling Along the Supply Chain

Passing legislation to handle the situation, however, and making sure that legislation is executed are two different matters. First, the consumer needs to be coerced. Electronics are not yet as easy to recycle as paper. Other than a guilty conscience, there is little to prevent an end user from simply dropping an old cell phone into the household trash. Some transfer stations do sort trash, but many do not; and the likelihood of any one consumer being tracked down for inappropriate disposal of goods is slim. Some corporate entities have been fined for improper disposal of light bulbs and other items, however. And trash haulers are sometimes fined for not properly separating recyclables from other waste.

Farther back in the supply chain, the manufacturers, for their part, are encouraged or required by current legislation to provide recycling programs, but they cannot generally force consumers to carry through. For the time being at least, much of this legislation lacks teeth. "It's a tangled area," says Kimberly Allen, principal of Pañña Consulting, adding that to further complicate matters, the EU has its own rules, whereas in the U.S., recycling legislation varies by state.

Companies such as Dell, HP, and Apple now have programs in which consumers can exchange, drop off, or ship off old units. Each of these manufacturers has a Web site dedicated to the ins and outs of recycling procedures, depending on where you live and what product you wish to recycle. Because the logistics of getting units from point A to point B might be beyond the scope of a given manufacturer, a number of third-party coalitions and businesses have sprung up that exist to provide these services. But here, as in much of the current recycling ecosystem, the waters are murky. Some, though not all, electronics end up in landfills in developing nations, where they may be taken apart by indigent labor under less than ideal conditions. The Basel Action Network (www.basel.org), a group dedicated to globally responsible recycling, now offers third-party audited certification of recyclers, including a directory where interested parties can find an authorized recycler.

Product Postmortems

That developing nations are more eager for used electronics than their economically better-off counterparts says something about the current value statement, or lack thereof, of electronics recycling. Says Allen: "The business case isn't super clear. There are challenges with how to collect products and disassemble them." Each component of a display or other electronic device needs to be separated and handled differently in order to be recycled. Consider a CRT TV, for example (and there are many such TVs still awaiting disposal). Some of these, according to a 2008 Popular Mechanics article (http://www.popularmechanics.com/technology/how_to/4277703.html), find new life as refurbished CRT TVs in markets where CRTs are still desirable. Otherwise, the glass picture tubes, which contain lead, can be melted down to be reconstructed into new CRTs or sent to lead smelters. Circuit boards in TVs are non-biodegradable, but can be recycled. Companies specializing in this work are able to remove about 99% of the precious metals from the circuitry on the boards by shredding them and extracting the metals. It is also possible to desolder specific components from the boards for further use. Plain circuit boards can be reused as building materials. And plastics and metals in the television casing can also be stripped out and used to create new products.

In the case of LCD TVs, the CCFLs used for backlighting contain mercury but can broken down (again by specialty companies) and the glass and metal reused for various purposes. The LCD glass cannot be used to make more LCD glass (it is not pure enough) but can be repurposed into a variety of building materials. Some experts have even suggested that the polyvinyl-alcohol (PVA) coating on the LCD glass can be used for various health products because PVAs are helpful in tissue-regrowth applications. Applications for recycling LEDs, which are increasingly used to backlight LCD TVs, are not numerous yet, but the general consensus is that because they contain no mercury, they will be easier to handle and repurpose.

So, there are plenty of useful components to be gleaned from old displays, but separating them from each other is yet another part of the puzzle. When components are soldered, glued together, etc., it can be difficult and time-con

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guest editorial

Display Manufacturing on Flexible Substrates

by Greg Gibson

The vast majority of commercially available displays and related touch-screen technologies are currently manufactured on rigid glass substrates. For mature display technologies such as AMLCD, the consumer expects continued increases in display size and performance, with a simultaneous reduction in product price. These requirements are typically met both by advancements in the display technology and by continued improvements in display manufacturing. For emerging display technologies such as OLED, the focus is on commercialization, supported by manufacturing processes that can ultimately be driven down in cost to a point that supports the introduction of competitive mainstream products. The vast majority of these commercially available and emerging displays, and related touch-screen technologies, are currently manufactured on rigid glass substrates, which offer many advantages for both the final display product and the process steps used to manufacture that product.

However, display manufacturing on flexible substrates is a technology segment that is receiving increasing amounts of development and investment. The move toward flexible substrates is typically driven by the requirements of the final product, for instance, a flexible plastic display, or the efficiencies that can be realized when the manufacturing process can be executed on flex. Certainly, the recent market success of e-books has been a significant boost to the electrophoretic-display segment, but it is believed that additional market penetration can be achieved if this technology can be commercialized on flexible displays. Such a display, and the resulting end product, could be thinner and lighter than the glass-based product, while offering significantly increased resistance to breakage. Manufacturing on flex can also enable products with performance and cost points that simply could not be met by using glass.

The ultimate target of flexible-substrate manufacturing is, for many, the migration to a complete roll-to-roll (R2R) process, where most if not all of the manufacturing can be executed in a continuous or semi-continuous fashion. The promise of significantly increased throughput and reduced manufacturing cost is alluring, and indeed R2R manufacturing on flex has been demonstrated for certain applications such as cholesteric displays and electronic skins. However, for most flexible-display applications, there are many technical challenges preventing widespread migration to R2R, not the least of which is the difficulty in maintaining dimensional control and pattern registration accuracy on flexible plastic, and the general challenge of integrating a wide range of processes into a continuous line.

Flexible substrates can also be processed in a single-substrate manner, using either a carrier plate or in a free-sheet form. By using the carrier plate approach, the flexible substrate is attached to (or built on top of) a rigid glass carrier panel. This carrier plate (CP) is typically display glass that is matched to a standard AMLCD Gen size, thus taking advantage of the wide range of process equipment that is already available for display processing. Even so, the manufacturing equipment, and the processes performed, must be adapted to the unique characteristics of the laminated-carrier-panel/flexible-substrate assembly. In addition, there are special requirements for the ultimate separation of the flex substrate from the carrier and the final assembly of the flexible-display device. Despite these challenges, the CP approach offers the advantage of maintaining reasonable dimensional stability and overlay accuracy during

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PUT THE BEST ON DISPLAY

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Award winners will be profiled in the SID Show Issue of *Information Display Magazine*; as well as included in SID's comprehensive global publicity efforts surrounding the show.

DISPLAY WEEK SID

president's corner

The Importance of Light

Paul Drzaic
President, Society for Information Display

I'm a student of light. If that statement sounds confusing, please allow me to explain. One of my hobbies is photography, and particularly outdoor photography. I am fortunate enough to live only an hour or so from the California Big Sur coastline, where the word "amazing" is an understatement when describing the views available along Highway 1. The same scene can look very different from day to day; sometimes even from hour to hour. The position of the sun in the sky changes the color of the illumination and the depth and position of shadows. The absence or presence of clouds, fog, and rain, or even the wind kicking up ocean spray can change how light interacts with the ground and what I'm able to see or photograph. Most of the time, the lighting is out of my control, other than what I can do by paying attention to weather forecasts and what times the sun rises and sets.

Working in the electronic-display industry also makes me a student of light. In the case of displays, though, the quality of the light provided by the display is determined by a series of compromises inherent in whatever technology is being used in the display. In most cases, the display just has to be good enough to provide the image that the user wants to see. Of course, what "good enough" means depends on the situation and setting. When watching a movie at home, I'd love a reasonable facsimile of what I'd see if I paid my $9.50 to the local movie theater. When getting a text message, I just need to be able to read the message quickly and without hassle. In these various situations, the display is part of a system that I expect to function in a certain way.

Still, advances in display technology time and again have provided strong, emotional responses that have helped pull products out of the lab and into the mainstream. High-pixel-count televisions, providing image clarity that people had never seen in televisions before; OLED displays in mobile devices, enabling a color gamut and contrast totally unexpected in small-format displays; pico-projectors, presenting color video imagery in places where one would never expect to see it. It is the extra benefits in shaping light provided by new capabilities in displays that generate these emotional responses and drive new waves of products.

For my photographic hobby, as well as for my work on displays, there are a few things I am still waiting for that would improve my interaction with light. How about a camera-viewing screen that I can actually use outdoors in bright sunlight? Maybe this is an application of that color e-paper product we are all waiting for. Or, a display that renders my photographs with a color gamut closer to the real scene, so the last temptation to print the photograph finally goes away – is this an OLED, LCD, PDP, plasma, or something else? These are products that would reach me on an emotional level and probably induce me to upgrade my equipment (once again!) before I really need to. ■

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2.4"	240 x RGB x 320	262k / 16.7M	36.72 x 48.96	42.00 x 58.60 x 1.65	200
2.8"	240 x RGB x 320	262k / 16.7M	43.20 x 57.60	49.10 x 67.30 x 1.75	200
3.4"	480 x RGB x 272	16.7M	74.88 x 42.43	82.80 x 54.30 x 1.60	200
4.3"	480 x RGB x 272	16.7M	95.00 x 53.80	103.50 x 67.00 x 2.05	200
7.6"	800 x RGB x 600	16.7M	165.60 x 99.36	177.30 x 118.32 x 5.40	200

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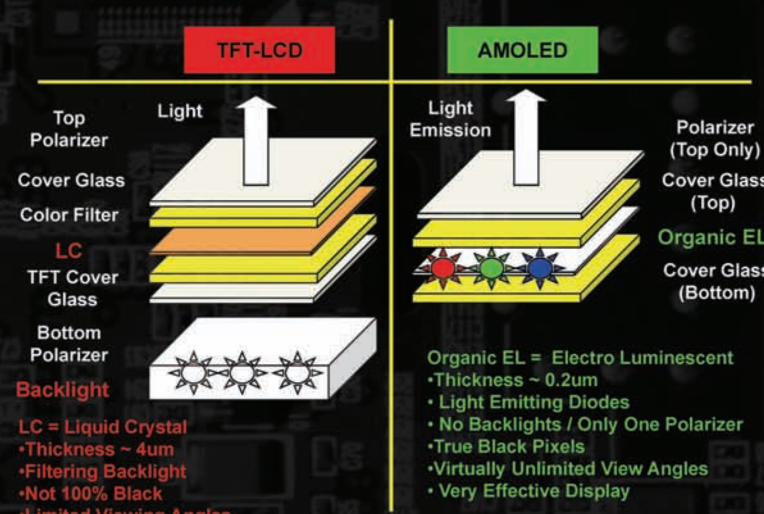
TFT-LCD vs AMOLED



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Flexible e-Book Displays Produced in Standard TFT and Module Factories

Thin, light, and robust flexible e-book displays are being prepared for mass production with most of the same equipment and processes used for glass displays.

by Ian French

THE FIRST e-BOOKS, such as the Rocket and Softbook reader in the 1990s, were not major commercial successes. This was probably due to a combination of limited reading material being available, poor content distribution, and the fact that these devices used active-matrix LCD screens that did not prove popular for immersive reading. In the last few years, there have been major developments that have led to wider acceptance of e-books. First, high-quality electrophoretic displays were created that closely mimicked the visual appearance of printed paper. Then, Amazon, Sony, and other companies developed the infrastructure to make large numbers of books, newspapers, and magazines quickly and easily available, either by wireless or via the Internet.

Electrophoretic displays had been under development by several groups since the 1970s, but by the early 1990s they had largely fallen out of favor because of the rise of LCDs and the many practical problems associated with making high-quality electrophoretic displays with acceptable performance and lifetime. In 1995, the Jacobson group at MIT revisited electrophoretic-display technology and developed a foil with microcapsules containing black-and-white particles with opposite electrical charges on them in a clear liquid. The particles could be moved by external electrical fields, so that either the black or white ones were toward the top, or they could have different degrees of mixing within the capsule. An observer would then see the capsule as black or white, depending on which type of particle was uppermost, or a shade of gray that depended on the distribution of mixed particles. Along with good control of the surface chemistry of the charged particle, this approach solved many of the pre-existing problems of electrophoretic displays.[1] The development of electrophoretic foils was spun out from MIT just 2 years later when the E Ink Company was formed in 1997.

Ian French is principal scientist at PVI, concentrating on the industrialization of EPLaR. He worked at Philips Research for many years on a range of display and sensor applications. He can be reached at ianfrench @pvi.com.tw.

To make high-resolution e-book displays that can show pages of text and monochrome pictures, E Ink foils are laminated onto amorphous-silicon (a-Si) TFT backplanes of the type used in most active-matrix LCDs. The first e-book to use E Ink foils was the Sony LIBRIé, which was launched in 2005. Initially, TFT-backplane manufacturing and module integration were carried out by Philips, but these activities were passed over to Prime View International (PVI) late in 2005 when Philips decided to stop manufacturing displays.

Currently, the e-paper market is one of the most dynamic in the display industry. Market-research-company DisplaySearch estimates that it will grow from a value of $100 million in 2009 to $9 billion in 2018. It is ironic that this dramatic growth is based on a technology that would seem like a backward step if we only consider the usual display metrics of brightness, contrast ratio, color gamut, and speed of response. Electrophoretic displays have slow response, a lower contrast ratio than LCDs, and, at the moment, they are only monochrome. On the positive side, they benefit from long battery life because they only draw power when the page is rewritten, but their major attraction is their paper-like appearance.

Although e-books have captured much of the visual experience of the printed page, their feel is very different. This can be important for immersive reading, which people typically do while holding a book, magazine, or newspaper. At the moment, the e-book displays have a rigid, glass TFT backplane that must be enclosed in a metal case for protection. This makes them comparatively heavy, particularly for larger displays, such as 8 in. and above. They are well protected by the metal case, but they can still sometimes break if they are dropped or if an object presses hard against them, as can happen in a bag. The obvious solution to these issues is to replace the glass backplane with an array of TFTs on a plastic substrate to make the display thinner, lighter, and more robust. In fact, it was so obvious that E Ink first started working

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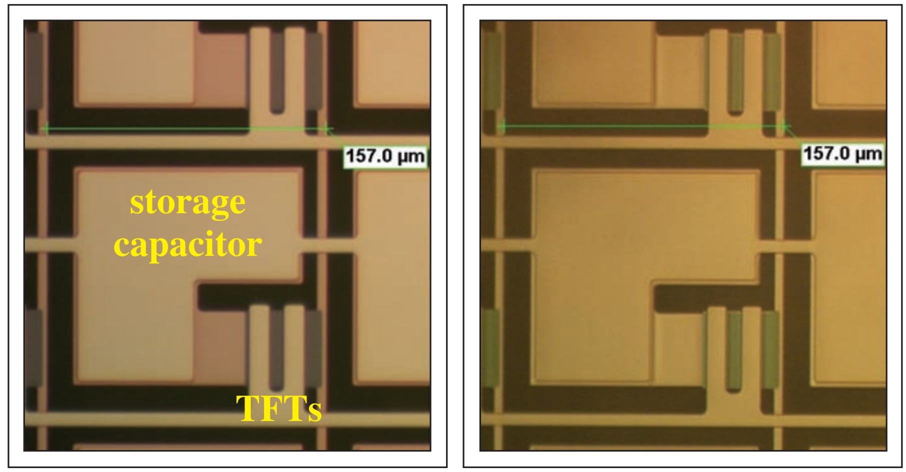
with Lucent Technologies to make flexible displays with organic TFTs on a plastic substrate as long ago as 1999. Since then, E Ink has demonstrated high-quality flexible displays, with more than 10 different companies and research institutes using a range of different TFT types, flexible substrates, and fabrication techniques. Surprisingly, given that so many companies have successfully made good demonstrators over the years, flexible displays have still not reached the market. One of the main reasons for this is that many of them were made using experimental techniques on small substrates that would have required large investments in new machines and methods of handling in order to scale up to mass production. Organic or plastic TFTs also require new materials systems that have not yet made it into commercial products, despite having been in development for use in TFTs for more than 10 years.



(a) (b)

Fig. 1: These photographs of electrophoretic-display pixels were taken through the substrate: (a) on glass and (b) taken through a laser-released EPLaR polyimide substrate.

The EPLaR Process

The electronics on plastic by laser release process (EPLaR)[2] is one method that can be used to produce flexible displays. (It is the method that has been adopted by the author's company, Prime View International.) This process employs more than 95% of the same steps and equipment that are used for making glass e-book displays, which minimizes investment cost and development time because no new factory is needed and relatively few new process machines have to be purchased. EPLaR displays also directly benefit from years of experience of manufacturing and using glass displays in e-books.

The main steps in making active-matrix electrophoretic displays on glass involve a-Si TFT-array fabrication, followed by display-module assembly. A field-shielded pixel structure having a relatively thick polymer insulator over the TFT is used. This allows the ITO pixel to lie over the TFT, rows, and columns, maximizing the ITO area and therefore the area of the electrophoretic foil that is being controlled. This is the same TFT structure that is used in LCDs with large-optical-aperture pixels. The steps in module making are scribe and break to separate the displays on the motherglass; lamination of an electro-phoretic foil; attachment of row and column drivers by a chip-on-glass process; and then, finally, attachment of a flexible printed circuit board (PCB) to provide connections to external driver electronics.

The EPLaR process closely follows that for making glass electrophoretic displays, but with some additions. The first extra step is inserted before TFT-array fabrication. A 10-µm-thick polyimide layer is applied to a standard glass substrate. This will eventually become the plastic substrate. As long as the correct interface treatments are used in conjunction with the correct type of polyimide and curing schedule, then the polyimide adheres very strongly to the glass substrate. The polyimide can withstand all of the standard processes used for making TFTs on glass substrates.

To reduce the level of particles and contamination, all TFT factories minimize the number of workers inside them by using integrated automated handling systems. These use cassettes on automated guided vehicles for carrying the glass substrates between process machines. The substrates are transferred from the cassettes to processing machines, and between adjacent process stations, by robotic arms. The glass substrates are so large, even for Gen 2 factories, that they sag in the cassettes, and the spacing must be very accurately controlled to obtain the maximum number of displays in a cassette while still allowing the pick-up arm of the robots to get between the substrates. The automated handling is so precise and finely tuned that, in the past, factories have not been able to change glass-substrate thicknesses from 1.1 to 0.7 mm because all of the cassettes and handling systems would have needed to be changed. This illustrates the kinds of difficulties that should be expected if major changes are made to the size and weight of substrates in TFT factories. In the EPLaR process, the polyimide increases the substrate thickness by only about 1.4% and the weight of the substrate by less than 1%. These small changes allow EPLaR substrates to be used with all of the existing automated handling and mass-production equipment in TFT factories.

During processing, the polyimide layer is strongly anchored to the glass substrate. This means that the design rules for EPLaR displays can be kept exactly the same as for TFT arrays on glass, allowing use of the same mask sets for making glass and EPLaR displays. Figure 1(a) shows a photograph of a pixel of a glass electrophoretic display and Fig. 1(b) a pixel from a flexible display made by the EPLaR process. It can be seen that they are identical, except for the color, which comes from the thin polyimide. In comparison, flexible displays made on relatively thick pre-formed plastic substrates must use design rules that allow for shrinkage and swelling during processing because the substrate absorbs moisture and loses it during heating. For this reason, relatively thick pre-formed plastic substrates are generally not so well-suited for making high-resolution displays.

Electrophoretic foils, driver chips, and electrical interconnects are laminated onto the substrates after TFT-array fabrication with the

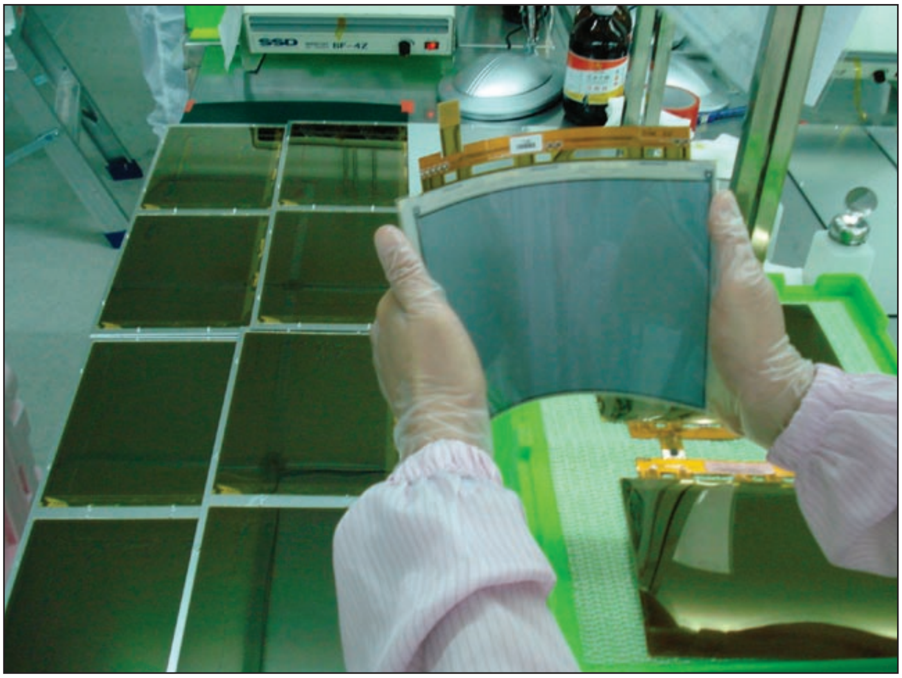


Fig. 2: These 9.7-in. flexible displays have just gone through laser release. The ones on the table and in the carriers are face-down while the one being held has the front face of the display toward the camera.

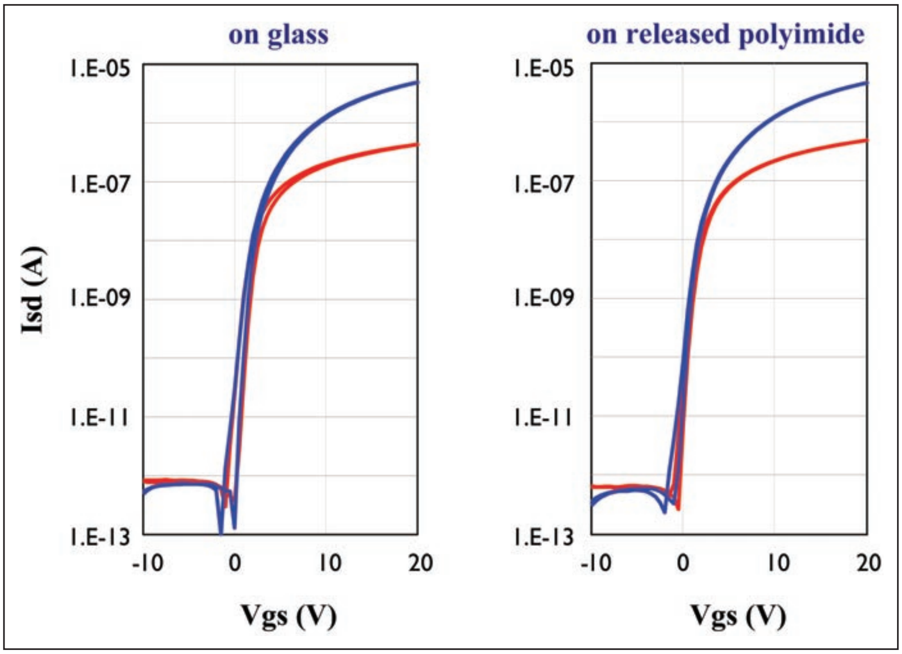


Fig. 3: The graph on the left shows the transfer characteristics of test a-Si TFTs on glass and the graph on the right, on an EPLaR display.

same equipment and process settings that are used for glass electrophoretic displays. At this stage, there are fully working electrophoretic displays on glass, but with a thin polyimide layer between the glass and the bottom of the TFT array. To make them into flexible displays, the second additional EPLaR step is needed. The polyimide is released from the glass substrate using a laser process, and the polyimide becomes the plastic substrate for the flexible display. Figure 2 shows part of a batch of 9.7-in. EPLaR displays immediately after laser release at the PVI module factory in Yangzhou, China.

Electrical Characteristics

Electrical characteristics measured on test TFTs from a standard glass substrate and an EPLaR display after laser release are shown in Fig. 3. The TFT characteristics are effectively identical and no significant difference in ON-currents, threshold voltage, sub-threshold slope, or OFF-currents are detectable. All of these characteristics are important because together they determine the drive voltages and timing needed to drive the display. For instance, TFTs with a small sub-threshold slope have a wider voltage difference between their OFF and ON states, so that more expensive driver chips with a larger voltage range are needed. The other TFT characteristics all affect the driver voltages and timing in some manner. The same drive electronics and drive schemes can be used for glass and EPLaR e-book displays because of their identical characteristics, which is a significant advantage to a company that is manufacturing both.

DC-stability measurements at elevated temperatures and high gate fields were also made on glass and EPLaR TFTs. Again, the results were identical for laser-released EPLaR TFTs and test devices on glass. The results show that TFTs in EPLaR displays will have the same performance, lifetime, and stability as a-Si TFTs in LCDs and e-books.

EPLaR Displays and Future Plans

All active-matrix displays that are already in mass production use glass as the TFT substrate. This includes TFT-LCDs, active-matrix OLEDs, and e-books. EPLaR displays are called flexible to indicate that they are not rigid in the same way as glass displays are; instead they are thin, light, and robust. Initially, EPLaR displays will be used in applications where they are held flat or curved to a fixed shape, rather than ones in which they are constantly rolled and unrolled. In the past, E Ink has described displays that have the feel and thickness of a mouse pad to convey the idea of a robust display that is normally used flat, but that can withstand a certain amount of bending. There is no reason why EPLaR displays should not be made rollable in the future, but this would require a redesign of the module, especially the placing of the rigid row and column drivers, and extensive mechanical testing.

PVI has made EPLaR displays with 1.9-, 6-, and 9.7-in. diagonals, which are three of the standard sizes the company already uses for glass electrophoretic displays. Figure 4 is a photograph of an EPLaR 9.7-in. display without a case, showing the image of a newspaper page.

Although the EPLaR process has been developed primarily for use in e-books and e-newspapers, it will also allow other applications to benefit from having thin, light, and robust displays. One obvious possibility is incorporating a small display into a smart card to show customers account information and maybe alternate between the customer's photograph and signature during payment. Glass displays cannot be used in smart cards because they are too thick and rigid, but EPLaR displays can be less than 0.4 mm thick. Small flexible displays could also be used as electronic shelf labels that do not break when knocked by a can or bottle, or for secondary text displays on mobile phones. Figure 5 shows a photograph of a 1.9-in. EPLaR display having drive electronics on a flexible PCB that has been attached to a shaped holder to demonstrate that it can conform to a curved shape. The image on the EPLaR screen has 16 gray levels, and it is easy to see that it could act as an ID photograph in an electronic badge. The electronics and drive scheme for this portable demonstrator were made by MpicoSys.[3]

EPLaR displays are currently being readied for commercial release, with production split between the PVI TFT factory in Taiwan and the module factory in China. The electrical characteristics and stability of the a-Si TFTs on EPLaR displays are the same as TFTs made on glass for LCDs, which have been used in many millions of devices, ranging from mobile phones to LCD TVs. EPLaR displays can be used in a range of products, such as e-books, e-newspapers, smart cards, and electronic shelf labels. In the future, they will benefit from planned improvements in electrophoretic displays on glass, such as the development of full-color displays and video rates, which will also be applicable to EPLaR displays.

Fig. 4: *This 9.7-in. EPLaR display is flexible, though not rollable.*

Fig. 5: *This 1.9-in. EPLaR display in a curved holder can hold this shape indefinitely.*

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High-Volume Manufacturing of Photonic Components on Flexible Substrates

The penetration of photonic technologies into the low-cost consumer-electronics marketplace has so far been limited. This article details several flexible-substrate-based manufacturing processes that have been developed for the high-volume low-cost production of optical waveguides – key components of a specific optical touch-screen system.

by Robbie Charters

THE RAPID INCREASE in functionality of handheld electronic devices has put significant pressure on standard keypad interfaces to the point that touch-screen interfaces on mobile devices are now a common feature. In addition, the release of Microsoft Windows 7, with its strong touch-application focus, looks ready to make touch screens pervasive at larger screen sizes.

Attractive features of any touch-screen technology include low power consumption, double-touch-pen and/or gloved-finger operation, and freedom from distortion of the liquid-crystal-display (LCD) optical performance through absorbing overlays or films. One class of technology that exhibits all of these features is optical or infrared (IR) touch.[1] In this approach, a grid of IR light beams is constructed, propagating just above the top surface of the LCD. Any touch event breaks the beams, casting a shadow that can be detected by electronic means. Figure 1 shows the typical configuration for an IR touch screen, in which the beams are set on a Cartesian grid and discrete emitters and receivers are mounted in one-to-one correspondence around the edge of the LCD.

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An alternative approach, developed by NextWindow, uses point-source corner-mounted emitters to create a spherical coordinate system for IR light beams and camera-based detection. More recently, RPO, Inc., has introduced Digital Waveguide Touch (DWT), in which a series of densely packed light pipes, or optical waveguides, are employed to route LED-generated IR light from the touch-screen grid on the perimeter of

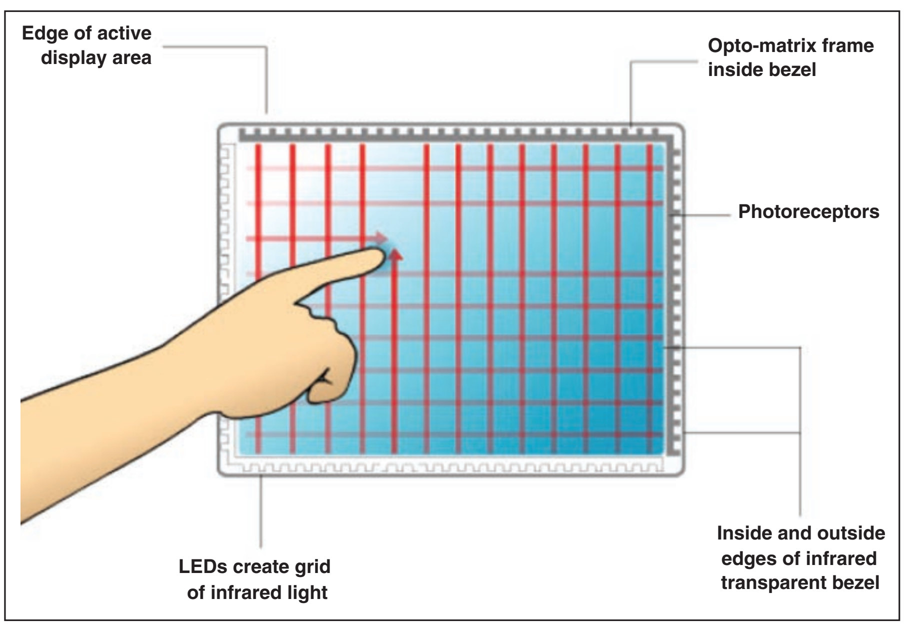

***Fig. 1:** In this typical optical-touch-technology configuration, LEDs arranged along two edges create a grid of IR light and discrete receivers (photoreceptors) are mounted in one-to-one correspondence around the opposite edges of the display. Illustration courtesy Elo TouchSystems.*

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the LCD to remotely mounted cameras. The elements of a DWT-based touch screen, shown in Fig. 2, are described below.

The DWT touch-screen module is assembled around a central rectangular LCD panel with the waveguides mounted to the bottom and left edge of the touch-screen assembly. Infrared light is emitted by two LEDs, with each divergent IR light beam striking a parabolic reflector on the opposite side of the assembly. The light beams are collimated by the reflector along the top and left edges of the assembly and reflected back over the top of the LCD panel as a 300-μm thin sheet of IR light projected over the glass surface. The collimated light is captured by the waveguides on the opposite sides of the assembly. Each waveguide channels an independent light path to one or more pixels on an application-specific integrated circuit (ASIC) based light-sensor camera.

This waveguide-based light-distribution circuit offers a distinct advantage over existing optical touch systems by reducing the number of emitters and receivers, thereby dramatically reducing costs and power consumption. In addition, the miniaturization of the optical components afforded by the waveguide-based approach results in narrower, more aesthetically pleasing borders (bezels) around the LCD. However, the key advantage of DWT lies in its ability to accurately pattern waveguide and micro-optic lens components in a single photolithographic step. This simple mask-based process completely defines the touch-screen resolution, ambient light rejection, and sunlight operation of the system. A change in touch-screen performance or screen size is simply a matter of changing the mask design layout, a routine CAD operation. A description follows of how the DWT waveguide components can be manufactured in high volume on flexible substrates and of how different techniques have been applied for the automated handling of these substrates.

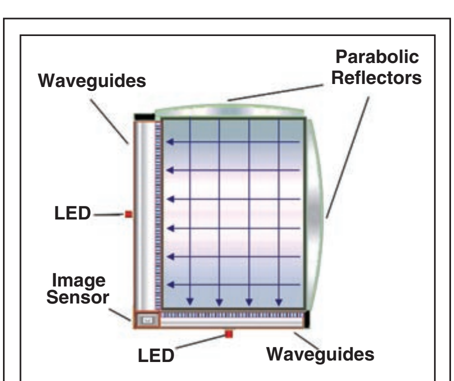

Fig. 2: An optical waveguide approach to touch uses just two LEDs (bottom and left) for IR light. (Drawing components are not to scale.)

Waveguide Manufacturing

The basic processing steps for manufacturing waveguides for DWT are shown in Fig. 3.

In the first step, a planarization layer of low-refractive-index waveguide buffer material is applied with high uniformity to a flexible substrate. This layer is flood-exposed under UV light to form both a mechanically flat surface for subsequent coatings and also the base section of low-refractive-index material that forms the waveguide cladding. In a second step, a high-refractive-index waveguide material is coated directly onto the buffer and is selectively exposed to UV light through a photomask. The unexposed material is then removed through a simple wet-develop process.

As mentioned above, the waveguides and microlens components formed in this single photopatterning step completely define the DWT touch-screen performance. The resulting photopatterned waveguide core features enable the guiding of light in the same manner as the familiar optical fiber through total internal reflection of light at the interface between the core and cladding materials.

In a final step, another low-refractive-index cladding material is overcoated, which planarizes and encapsulates the core features. For DWT, this third layer is also aligned and photopatterned with large-area features that open air gaps over core-patterned microlens surfaces. In a final processing step, individual waveguide die are singulated from the substrate using a dicing process, at which point they are ready for assembly into DWT touch-screen modules. By design, the waveguide manufacturing process itself is similar to a photoresist photolithography line.

Polymer Waveguides

Polymer waveguides have been an active area of research for many years. The pioneering work of a group at Allied Signal laid the

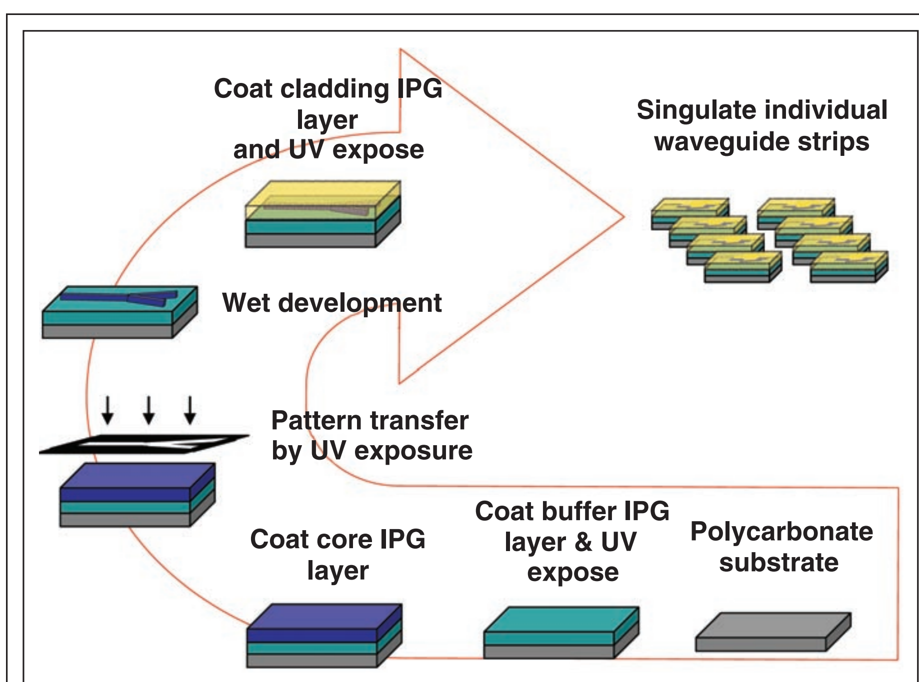

Fig. 3: A polycarbonate substrate (lower right) is the foundation for the waveguide manufacturing process, which ends with individual waveguide strips (upper right). IPG stands for RPO's Inorganic Polymer Glass.

ground rules for the design of polymer materials for optical applications, with a strong focus on long-haul telecommunications.[2] In that case, highly fluorinated acrylate-based materials were used with silicon-wafer substrates and standard semiconductor processing tools to manufacture high-performance waveguide components. In addition, the large thermo-optic coefficient of these materials allowed highly efficient, electrically tunable devices such as space switches and variable optical attenuators to be demonstrated. Today, polysiloxane-based material systems are also recognized as well-suited to optical waveguide and thermo-optic tuning applications, due to their low optical loss and high environmental stability.[3]

Designed and manufactured by RPO, Inorganic Polymer Glass (IPG) coat materials are polysiloxane-based systems, originally developed with long-haul telecommunications applications in mind. These materials exhibit, among other desirable features, low optical loss at telecommunications wavelengths, an accurately tunable refractive index over a wide range, matched thermo-optic coefficients, and low glass-transition temperature (T_g). Of these, a low T_g outside the operating temperature range of the waveguide component is vitally important to negate the buildup of internal stresses and possible micro-cracking within the materials during any thermal cycling in product use. Indeed, IPG materials are designed to have no material phase transitions within the DWT operating and storage temperature ranges. The IPG materials are therefore always in a rubbery state, also a very important feature for waveguides manufactured on flexible substrates.

IPG materials are manufactured as an oligomeric mixture such that the materials can be coated as films from a viscous, solvent-free resin. By controlling the IPG synthesis process and molecular design, the molecular-weight distribution of the resin can be tuned to combine effective coating properties and high environmental stability with low-volatile outgassing. The solvent-free nature of the coat fluids is a key feature for use with plastic flexible substrates – swelling of the substrate due to the presence of a carrier solvent, even for short periods of time, is never encountered. Indeed, since there is no solvent to bake out, a soft bake step is completely unnecessary. In addition, since there is no solvent evaporation during coating, very high-quality optical films with low surface roughness can be easily formed through techniques such as extrusion coating, spin coating, or extrude-and-spin. On the flipside of these positive features, IPG materials remain a viscous liquid even in film form until exposed to UV light, which presents challenges from a substrate-handling perspective, particularly for fully automated production lines.

Flexible Substrate Requirements

The application of optical waveguides and photonics to consumer-electronics products, such as DWT, requires careful consideration of manufacturing costs, certainly compared to the typical telecommunications products that polymer waveguides have historically targeted. DWT waveguide chips are generally large, rectangular die, a couple of millimeters wide and many tens of millimeters long, dependent on LCD screen size. The packing density of DWT die onto round wafers, whether they are silicon or a cheaper alternative, is severely limited both by geometry and overall substrate size. The use of the rectangular, large-area substrate sizes commonly found in the LCD industry are far better suited to DWT waveguide production, as a significantly higher volume throughput is achievable for the same processing time as a wafer-based process. The current RPO waveguide production process uses 400 × 500-mm-sized substrates (Gen 2.5).

The choice of substrate material is unusual in the flexible substrate world in that the substrate itself has no obvious functionality other than as a carrier, and, in fact, DWT does not use the flexible nature of the substrate at all. The sole reason that RPO chose flexible plastic substrates was to keep product costs low. In addition, the substrate and waveguides only reside in the bezel of the LCD, with no requirement for substrate optical clarity or quality.

The obvious requirements of DWT waveguide substrates are that they are flat enough to enable high-resolution photolithographic printing, have sufficient surface quality to allow a planarizing layer to be coated onto one surface, and, most importantly, are inexpensive. The very-high-performance flexible substrates, such as PEN, developed specifically for flexible-display applications, are unnecessary for DWT; low-cost standard substrate film materials such as PET, polyimide (PI), or polycarbonate (PC) are sufficient.

On closer inspection, however, there are additional features that need to be added to the substrate to allow successful production processing and also provide high-performance DWT operation. First, the photolithographic processing of IPG waveguides for high-volume production requires high-intensity UV light of a specific wavelength spectrum, to achieve high throughput but also to counteract detrimental oxygen-inhibition processes within the IPG photochemistry. RPO has worked directly with a photolithography-tool manufacturer to develop a customized projection scanning tool for DWT waveguide component manufacture. These production systems operate at high UV intensities, and under these conditions, the photosensitivity of the substrate as well as that of the IPG materials must be taken into account. By correct specification of the substrate material properties, it is possible to control the substrate photosensitivity. Figure 4 shows the large improve-

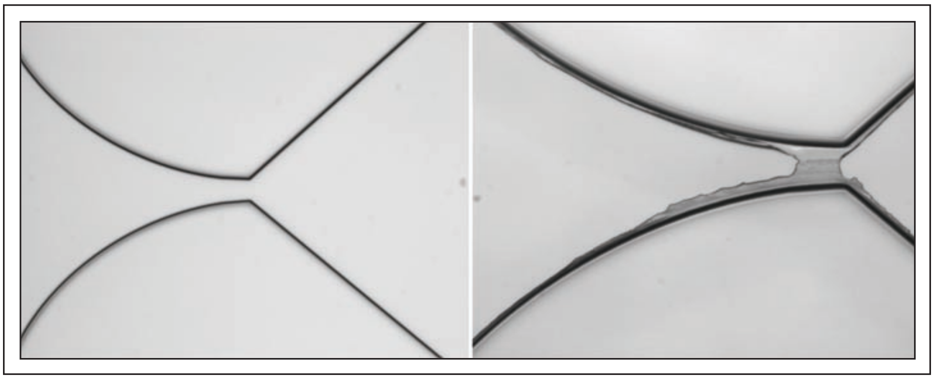

Fig. 4: *At left is shown photopatterning of IPG materials coated onto a substrate with correctly specified properties, and, at right, with a poor substrate choice.*

ment in photolithographic resolution of IPG photopatterned features that can be achieved with a correctly specified substrate.

Secondly, the sunlight performance of the DWT system as a whole is dictated by the amount of stray light that can reach the camera. This light is non-directional and therefore acts as a large background noise signal. The main source of this noise is ambient light that can travel through the substrate material to the camera rather than *via* the waveguide-defined path. Again, correct specification of the flexible substrate material properties allows control of stray light and can improve system performance markedly.

For DWT waveguides, however, the choice of base-substrate material is ultimately driven by the cutting process in which individual optical chips are singulated from the Gen 2.5 substrate, as shown earlier in Fig. 3. Unlike microelectronics components, in which surface contacts and pads located on the top surface of the die are usual, the most efficient use of photonic chips generally requires light to be injected or captured from the edges of the die. For polymer waveguides to be viable for consumer-electronics products, the singulation process must therefore provide an optical-quality chip endface in a single step – additional post-processes such as polishing are not viable.

Through judicious choice of substrate material, RPO has developed a single-step dicing process using high-speed diamond-impregnated blades similar to those used for dicing silicon wafers. When employed with a polycarbonate substrate material, very high-quality optical endfaces are achievable on waveguides with acceptably fast throughputs for volume production. This is in contrast to PET-type materials, in which the semi-crystalline nature of the substrate leads to high internal stress build-up and shattering/delamination of the waveguide layers during cutting. While PC is not as robust an industrial plastic as either PET or PEN, for example, the low temperatures involved in DWT waveguide processing, and the solvent-free nature of the IPG coat fluids, mean that PC is sufficiently well specified for the DWT application.

Automated Flexible Substrate Handling for DWT

While the manufacture of waveguides on flexible substrates is simple to achieve in a pilot-line process, the scale-up to fully automated production is dictated by cost requirements. Specifically, product cost structures dictate that it is not possible to handle the flexible substrates by the more usual approach of laminating to a rigid carrier such as FPD motherglass,[5] or by using rigid perimeter frames – rather, the flexible substrates need to be robotically handled as-is. Combined with the wet nature of some of the in-process IPG-coated substrates, this places restrictions on the type of robotic handling schemes that can be employed, and also on the design of the process-tool vacuum chucks that hold the substrate in place during processing. Of importance here is the choice of substrate thickness – the thicker the substrate, the less it will flex. However, it should be borne in mind that DWT waveguides occupy a space inside the LCD bezel, and with current LCD trends pushing to narrower and thinner bezels, keeping substrate volume to a minimum is important. Balancing these two counteracting effects leads to an optimum polycarbonate substrate thickness that is readily available in roll form.

Development projects between RPO and individual tool suppliers have resulted in a cohesive set of solutions for the handling of RPO flexible substrates. For all tools, the design of any substrate vacuum hold-down system requires that vacuum holes to the rear of the flexible substrate do not cause an appreciable distortion. This is particularly important for lithography tools where distortion of the substrate out of the focal plane can result in a reduction in resolution or changes in critical dimension of the waveguides. In addition, any through-holes in the substrate chuck that allow access for lift pins or pads must be carefully designed to avoid any resonant oscillation of the flexible substrate during processing.

Based on detailed finite-element analysis simulations, robot end effectors, cassettes, and spin-coat/develop chucks with integrated lift pads have been successfully designed, manufactured, and tested under continuous production conditions. Figure 5 shows a spin chuck with integrated lift pads in the raised position, allowing access for a robot end effector.

Extrusion coating is well established as the coating method of choice for large-area LCD screen manufacturing and is a key part of RPO's manufacturing strategy to minimize IPG material consumption. However, it presents further challenges for IPG coating of

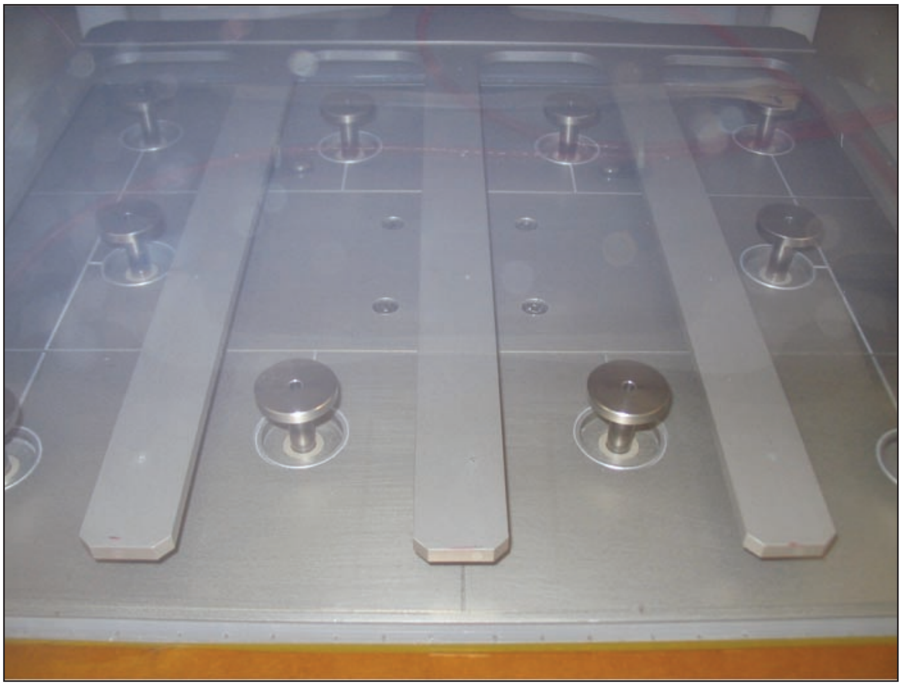

Fig. 5: *Above is an example of a flexible-substrate transfer paddle and spin chuck with integrated lift pads*

flexible substrates. During the IPG extrusion coating process, there is a measurable force from the fluid exiting the extrusion die down onto the flexible substrate; indeed, the proximity of the substrate itself causes a back pressure into the die cavity.

Additionally, the polysiloxane nature of the IPG materials necessitates a high-precision extrusion-coating process with accurately designed wetting surfaces and gaps. The flexible substrate must therefore be held flat with respect to the extrusion die with tight tolerances. These tight tolerances, and the potential of the fluid force to distort the flexible substrate over lift pad or vacuum holes, negates the ability to use the integrated handling solutions used for the spin tools. As a solution to this problem, a flexible substrate load station has been designed, using air to levitate the substrate and float it onto an interdigitated station where the end effector can raise the substrate and move it to the next process module. An image of the load station is shown in Fig. 6.

Summary

The high-volume manufacture of polymer waveguides on flexible substrates for DWT touch-screen applications is already under way. In particular, the choice of flexible substrate material allows for integration into a complete high-volume production solution for optical waveguides and planar photonic components for consumer electronics. Although pilot-production development work has been based on Gen 2.5 substrate sizes, all the techniques developed scale readily to larger substrate sizes and therefore greatly increased volumes. With minor detail modification to some of the process steps, this manufacturing process should be eminently suitable for scaling to roll-to-roll production.

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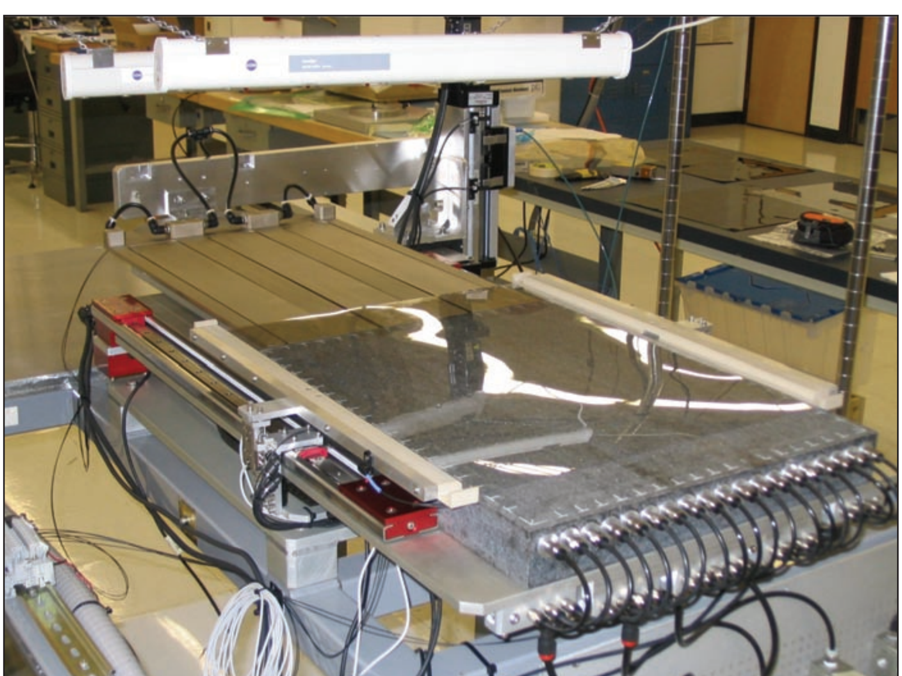

Fig. 6: This extrusion-coater flexible-substrate load station uses air to levitate the substrate.

Better Transmission: TFT-LCD Manufacturing Advances Reduce Cost and Energy Consumption

Much attention has focused on advances in TFT-LCD panel technology such as LED backlights, 120/240-Hz frame rates, wide viewing angle, and other technologies leading to performance improvements. But behind the scenes, TFT-LCD manufacturing continues to evolve, leading to increased manufacturing productivity, lower costs, and improved power efficiency. Recent developments include color filters, liquid-crystal alignment, and TFT design.

by Charles Annis and Paul Semenza

DESPITE THE FACT that TFT-LCDs use less power than similarly sized CRTs, the conversion to LCD TV has led consumers to choose larger and brighter TVs and is driving faster unit growth, which means the total power consumed by TVs is increasing. Worldwide, LCD TVs consumed an estimated 83 TWh of electricity in 2008, equivalent to the output of 11 nuclear power plants. That much electricity produced from coal-fired power plants would result in the creation of 66 million tons of CO_2. Much closer to home for electronics manufacturers, regulatory authorities in Asia, Europe, and the United States are writing and implementing power-consumption regulations for flat-panel TV sets.

At the same time, reducing costs is an essential goal for panel manufacturers to keep up with relentless price declines while trying to maintain positive margins. For larger TVs, average year-to-year cost changes during 2009–2015 are expected to range from –23% to –8%.

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Backlight Emphasis

In conventional LCDs, most of the light generated by the backlight is lost due to polarizer absorption, shading by the TFT-array aperture, color-filter absorption, as well as other factors, so that only about 5% of the light emitted reaches the front of the screen. Thus, even small improvements in transmission can enable significant backlight lamp reduction. For example, a 400-nit panel with a 5% transmission rate requires an 8000-nit luminance at the backlight; if transmission is increased to 10%, the same amount of brightness can be achieved with a 4000-nit backlight.

The backlight unit is the most expensive component of a display and accounts for 90% of the power consumption in large LCDs. This is the case regardless of whether the backlight uses cold-cathode fluorescent lamps (CCFLs) or light-emitting-diode (LED) lamps. Because LEDs are still substantially more expensive than CCFLs, increasing transmission is critical to enabling wider LED adoption for LCD-TV applications and is therefore currently a key theme in LCD manufacturing. Given the transmission's potential to reduce both cost and power consumption, a large variety of manufacturing technologies that target transmission increases are being developed and adopted for mass production. Methods such as low-resistance bus lines, C_{st}-less pixels, SHA, OA, PSA, thinner black matrix, and color-filter-on-array (all explained later in this article) are being implemented in the array, cell, and color-filter processes to increase efficiency.

Array Processes

Storage-Capacitor-Less Pixel Design: In TFT-LCDs, storage capacitors (C_{st}) are typically fabricated at each pixel to hold the voltage between writing data signals to the pixel. Without a C_{st}, the voltage can leak and change the state of the liquid crystal (LC). To prevent this, conventional pixel designs use an extra gate metal or wider gate line to increase capacitance. The trade-off is that the extra area for the gate line blocks illumination from the backlight. Samsung developed what it calls "C_{st}-less" pixels, which eliminate the storage capacitor and increase aperture ratio. Samsung has not publicly disclosed all the details on how it was able to achieve this, but it is likely that it was though a combination of improved LC and TFT performance. The company claims that transmission can be increased up to 10% with new pixel design.

Low-Resistance Bus-Line Materials: Adoption of low-resistance gate and data lines enables a reduction in the RC delay, which

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improves performance and can potentially

improves performance and can potentially eliminate requirements for dual-scan driving. In addition, due to lower resistivity, the width of the bus line can be reduced, which increases the aperture ratio without sacrificing performance. Because copper has a very low resistance, it is the material of choice. LG Display is already mass producing the majority of its larger panels using copper, and over the next 5 years copper and copper-alloy applications are expected to grow substantially.

Super High Aperture (SHA) with Organic Passivation: SHA pixel designs use a thick organic passivation layer to move the indium tin oxide (ITO) pixel electrode further away from the data line. Compared to conventional pixels, in which the ITO pixel electrode is separated only by a thin passivation layer, TFT capacitance is reduced. This allows the ITO pixel electrode to be extended over the bus lines, increasing the aperture ratio at each pixel. The technology has been used in mass production for a while, but is tricky to implement.

Cell Processes

The performance of LCDs is strongly affected by the orientation of the LC molecules, and LC molecules can be aligned in a variety of ways, depending on the LC mode. The LC molecules should be aligned orderly in the OFF-state and with an appropriate orientation or pre-tilt angle to facilitate switching to the ON-state when the drive voltage is applied to the pixel. Conventional LC alignment is achieved through the use of a thin polyimide layer (about 100 nm) on both the array and color-filter (CF) side of the cells. In the twisted-nematic (TN) and in-plane switching (IPS) modes, rubbing is used to create a preferred alignment direction during the cell process. In the PVA mode, patterning of the CF ITO common electrode is used to align the array pixel ITO electrodes in order to create fringe fields. In the multi-domain viewing-angle (MVA) mode, a protrusion is patterned on the CF to physically align the molecules, and a slit is created on the TFT side of the ITO pixel electrode.

Each approach has advantages and disadvantages. The viewing angle of the TN mode is limited. The TN and IPS modes offer higher transmittance, but rubbing is problematic because it generates particles and static electricity and is not easily scaled to larger substrates. The PVA and MVA modes are relatively fast and have good viewing-angle performance, but transmittance is lower, the LC material is more expensive, and the number of CF manufacturing steps must be increased.

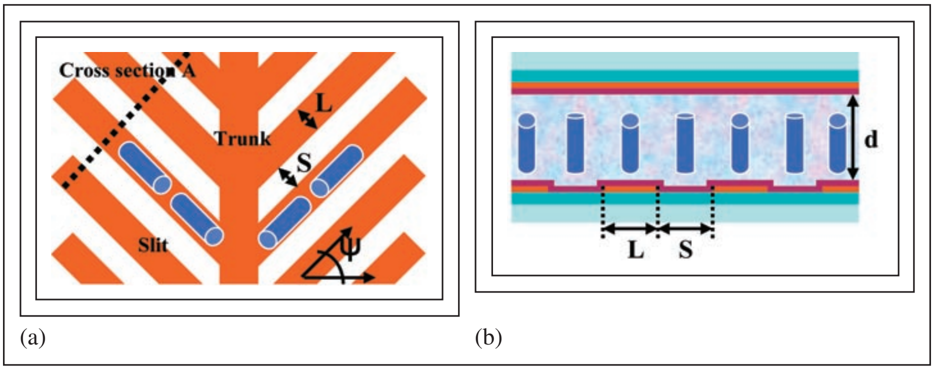

Fig. 1: *Above is a top view of an AMVA3 pixel electrode; below is the cross section. Source: AUO, SID 2009.*

For these reasons, developing new alignment technologies that enable higher transmittance, generate faster response times, avoid rubbing, improve contrast, allow a wide viewing angle, and offer more general productivity than conventional approaches have been longstanding goals for LCD makers. PSA and OA are two methods that achieve proper liquid-crystal pre-tilt angles without rubbing, protrusions, or patterned common electrodes.

Polymer-Sustained Alignment (PSA):

Typically, MVA panels use a protrusion to aid alignment of the LC; however, protrusions require an extra mask step in the CF process, which drives up cost and increases manufacturing time. Furthermore, the inactive area of the protrusion restricts transmittance of the panel and creates some light leakage that reduces the dark level and contrast ratio.

In polymer-sustained alignment (PSA) – also known as polymer-stabilized alignment or phase-separated alignment) – a polymer-alignment layer is formed over a conventionally coated polyimide by mixing a UV-curable monomer into the LC. The monomer is then activated by UV radiation while applying an AC voltage. The monomer reacts with the polymer layer to form a surface that fixes the pre-tilt angle of the LC. By removing the protrusion and achieving excellent LC pre-tilt alignment, the aperture ratio is increased, light leakage reduced, and LC switching performance is improved. Because this eliminates a protrusion from the CF side of the display, the contrast ratio is increased and the panel brightness can be improved by more than 20%. At the same time, costs are reduced because the protrusion mask step can be eliminated from the CF process and backlight lamps can be reduced.

PSA technology was originally developed by Fujitsu and is being used in mass production by AU Optronics Corp. (AUO), which has reported the development of a "protrusion-less" MVA-LCD that increases transmittance and reduces cost and process time. The company is calling the technology Advanced MVA (AMVA). The key PSA-related AMVA improvements are achieved by adopting a new "fishbone"-shaped pixel electrode in the array process and polymer-sustained alignment in the cell process to eliminate the protrusions of the conventional MVA mode (Fig. 1). When a drive voltage is applied to the fishbone electrode, LC molecules align along the direction of each domain.

In addition to the fishbone electrode, the other key PSA process modification is to add a monomer to the LC, which is then polymerized by UV curing in the cell process. This provides LC molecules with the proper pre-tilt angle for smooth and fast switching. The pre-tilt angle is fixed by simultaneously applying a voltage and UV exposure (Fig. 2). The pre-tilt angle of the LC can be controlled by the curing recipe by varying the applied voltage and UV dose.

The performance of AMVA is strongly affected by the material science of the polymer-alignment layer, monomer mixture, and LC. AUO has developed unique and proprietary materials to enable this new technology.

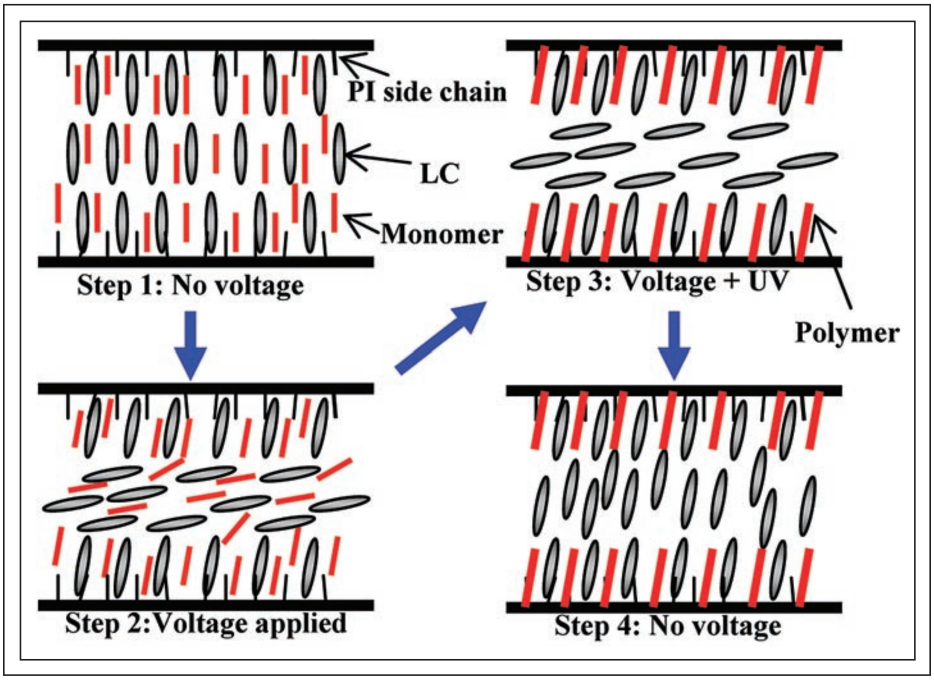

Fig. 2: *Steps 1–4 show the PSA polymerization process. Source: AUO, SID 2009.*

Optical Alignment: Optical alignment (OA) is the process of the interaction of light with a material that generates light-induced anisotropic properties. The anisotropy is determined by the intrinsic characteristics of the material and the direction of the anisotropy is related to the incident angle of the polarized light. For the material researched here, photoalignment involves photon absorption and interaction on a molecular scale, and the effects are observed in terms of the parameters of LC tilt angle, alignment direction, and azimuthal anchoring energy.

In optical alignment, UV exposure through a mask made of a special polyimide film creates an anisotropic feature that generates the pre-tilt angle. There are a variety of materials that have been researched that include azobenzene dyes or azo-dyes, poly (vinyl cinnamate), coumarin dye, poly-siloxane based polymers, and polyimides with additives such as cyclobutane. The basic principle involves the absorption of photons in the 200–365-nm UV range by the material that causes alignment of the polymer chains forming the layer through several processes, including isomerization, dimerization, and decomposition.

Some manufacturers have pursued a photo-decomposition approach. The advantage of this approach is that polyimides similar to those used in conventional processing can be adopted. UV light of sufficient energy breaks the organic bonds within the polyimide molecules, which create an anisotropy in the LC molecule alignment or a pre-tilt angle of about 2° (Fig. 3). The actual mechanism and photochemistry is apparently not well understood, but some sources have suggested it is a type of photo-oxidation. Historically, optical alignment approaches have been susceptible to long-term stability problems where the pre-tilt angle degrades over time. Overcoming this problem appears to be more closely related to the material composition of the polyimide alignment film rather than the process itself.

The benefits of OA are quite similar to those for PSA. Additionally, OA is assumed

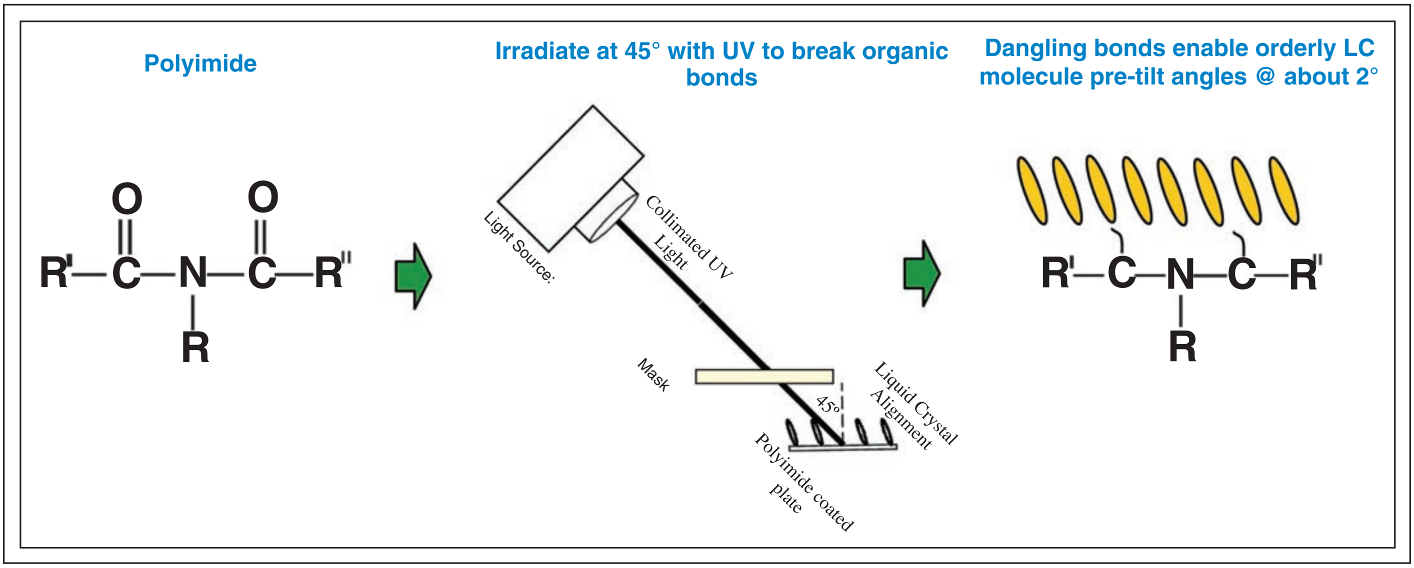

Fig. 3: *The OA process (left to right) results in LC molecules with a pre-tilt angle of about 2º. Source: Sharp Corp., adapted by DisplaySearch.*

to be highly productive and flexible, offering a wide process margin. The modifications to manufacturing are relatively simple. A photosensitive alignment film replaces the more conventional polyimides; the film is patterned on both the array and CF substrates in the cell process. Multi-domain structures can be achieved by patterning and the mask approach. The material is cured, then the substrates are conventionally aligned, scribed, and sent to module processing.

Sharp began mass-producing 32-in. eco-model TVs having OA in early 2009. In October 2009, the company announced that it will apply this technology to panel production at its plants in Sakai and Kameyama.[1] Refered to as UV2A (ultraviolet-induced multi-domain vertical alignment), the technology uses a combination of proprietary materials developed by Sharp and its partners with UV-exposure equipment and processing technologies. Sharp stated that its approach results in aperture ratios 20% larger than those of conventional panels.

Color Filter

Black-Matrix (BM) Width Reduction: In the CF process, panel manufacturers are reducing the width of the black matrix (BM). (Some width of black matrix is needed between the subpixels to block the light that leaks across from one subpixel its neighbor.) Similar to a reduction in the width of gate and data lines, a narrower BM translates into to a wider aperture ratio. Interestingly, the focus on improved transmission through thinner BM requirements has challenged other CF cost-saving technologies, such as ink-jet printing and BM ablation. Both of these have the potential to lower the total costs by reducing lithography-related-equipment and mask costs, but neither offer the same precise resolution and overlay performance as conventional photolithography that is required for very thin BM patterning.

Color Filter on Array (COA): COA is another CF-related manufacturing technology that moves RGB pixels from the common electrode glass to the array glass. There are multiple variations of this technology, but all increase transmission and improve contrast by widening the aperture ratio. However, moving color pixels to the array creates multiple process challenges – specifically, yield loss. For this reason, COA is not yet widely adopted. TMDisplay and Samsung are currently the two main producers of COA-based LCDs.

Greener Operation Equals More Green for Manufacturers: In order to continue profitable growth in an environment of continuous cost pressure and more-stringent environmental controls, TFT-LCD makers must simultaneously drive down manufacturing costs and reduce power consumption. The technologies that directly address these issues include those that aim to improve the historically low optical transmission of TFT-LCDs. Manufacturers that can bring such improvements into mass production will have a competitive advantage.

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[1]http://sharp-world.com/corporate/news/090916.html ■

Overview: Low-Temperature Polysilicon

Low-temperature-polysilicon (LTPS) technology is an important part of the active-matrix-LCD manufacturing environment. Will its role expand or has it found its niche?

by Jenny Donelan

LOW-TEMPERATURE-POLYSILICON (LTPS) appeared on the manufacturing scene about 10 years ago with the promise of enabling new generations of faster, higher-resolution slimmer LCDs. Since that time, LTPS has not exactly taken over from its counterpart, amorphous-silicon (a-Si), but it has developed a substantial position in the overall LCD market. Here's a look at how LTPS works, what it's currently being used for, and how it fits into the general LCD landscape, now and in the future.

The Promise of LTPS

LTPS technology enables the manufacture of active-matrix LCDs (AMLCDs) that are faster than displays using a-Si. "Fast" refers to the addressing speed: how quickly can a cell be accessed and receive a charge, and then how quickly can the process be repeated with the next cell? All this affects the frame rate, resolution and drive-complexity factors in a panel design. LTPS has many additional advantages: integration, smaller transistors, lower power consumption, and ruggedness. However, it is important to note that all these benefits are available on a sliding scale of sorts: LTPS allows smaller pixels, or faster large pixels, or lower power consumption, but not necessarily all at the same time.

LTPS transistors can be fabricated by recrystallizing amorphous silicon (a-Si) using laser annealing. With LTPS, you can achieve either a much greater current density compared to a-Si for the same size transistors, or have much smaller transistors for the same current density. These features enable designs in which polysilicon drivers are integrated on the glass, unlike a-Si, which generally cannot achieve this integration. This added capability of LTPS arises from the fact that its electron mobility can be as much as 100 times higher than that of a-Si, and hole mobility can be much higher than a-Si as well. Polysilicon consists of many small crystallites of silicon, with the crystal structure enabling high mobility. In contrast, the silicon lattice in a-Si has no crystal structure, so mobility is reduced.

The following discussion of polysilicon is from the article "Flexible Transistor Arrays" by Peter Smith, David Allee, Curt Moyer, and Douglas Loy, in the June 2005 issue of *Information Display*: "Another advantage [of polysilicon] is that CMOS circuits can be made in poly-Si because it is possible to fabricate both N-and P-type TFTs. Since CMOS is the dominant technology in the integrated-circuit (IC) industry, there is substantial experience in designing sophisticated integrated circuitry in CMOS. In stark contrast, only N-type transistors are possible in a-Si, making circuit design more complicated. N-type-only circuits have not been widely built in the IC industry since the 1970s, although N-type active-matrix backplanes are the mainstay of the display industry." (Readers are strongly

***Fig. 1:** These LTPS TFT-LCDs for notebook PCs from Toshiba Mobile Display range in size from 8.9-in. WXGA to 13.3-in. WXGA. Image courtesy TMD.*

***Jenny Donelan** is the Managing Editor of* Information Display *Magazine.*

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encouraged to review this and many other references for a complete technical summary of poly-Si technology).

Integration is key in that LTPS allows driver circuitry to be made part of the display. Because of its lower electron mobility, a-Si requires more extensive external driver circuitry that, in turn, must be made from conventional silicon. These driver types require external connections, although sometimes the driver chips can be put on glass without a separate PC board. Consequently, discrete logic chips must be mounted on printed circuit boards (PCBs) around the edge of the panel, a design that contributes to the overall bulk and expense of the display. The use of LTPS enables a smaller and more elegant panel layout (note the narrow rims on the displays shown in Fig. 1.)

Smaller transistors are possible for each subpixel due also to LTPS technology's higher electron mobility. The higher mobility reduces the size of the transistor for a given addressing time, and this feature can be used to increase the aperture ratio of the subpixel; *i.e.*, the ratio of transparent area to total area in each subpixel. This allows higher light-transmission efficiency that, in turn, enables brighter and higher-resolution displays (with *lower power consumption*).

The option of making a device *rugged* is one other distinct advantage of LTPS. Because the drive circuit can be integrated directly onto the glass surface, the number of potentially breakable connectors is decreased and the resulting LCD is vibration- and impact-resistant.

It is also important to note that when used as a backplane, LTPS is highly compatible with AMOLED displays. As Jennifer Colegrove, Director of Display Technology at DisplaySearch, puts it: "OLEDs are a current-driven type of display, and they need a lot of current." This is a requirement that is well-matched by the high electron mobility of LTPS.

High-Temperature and Low-Temperature Polysilicon

When display designers first began working with polycrystalline silicon, the standard methodology was to deposit a silicon layer on quartz, then heat it (using temperatures over 1000°C). The silcon would melt, and as it cooled, the crystals would reform in a uniform mode, creating a quartz semiconductor with much higher performance than a-Si. One of the drawbacks to this method, however, is that it is only possible to make a quartz substrate to a size of about 8 in., and it cannot be put on glass. High-temperature polysilicon (HTPS) has its place, however. Some manufacturers, such as Epson, use it for high-quality displays in projectors.

In the late 1990s, manufacturers began experimenting with using lasers in low-temperature annealing processes to replace the high-temperature annealing (the melting process described above). This allowed for the creation of larger displays that still had the basic electron mobility of the high-temperature process. And the low-temperature process had the added benefit of being usable with either glass or plastic. (While glass for displays can withstand about 500°C, plastic substrates are limited to about 200°C or less.)

LTPS products, most of them portable devices, began to be produced around 1998. In 1999, for example, Toshiba announced the world's first 4-in. VGA-resolution LTPS LCD. The "big three" manufacturers in LTPS today, according to Vinita Jakhanwal, Principal Analyst, Small/Medium Displays, with market-research-firm iSuppli Corp., are Sharp, Toshiba Mobile Display (TMD), and TPO Displays.

The Current State of LTPS

Jakhanwal notes that according to iSuppli, LTPS technology represents about 32% of the market share for active-matrix displays smaller than 10 in. (see Fig. 2).

Although a variety of large-screen LTPS TFTs have been produced, the technology

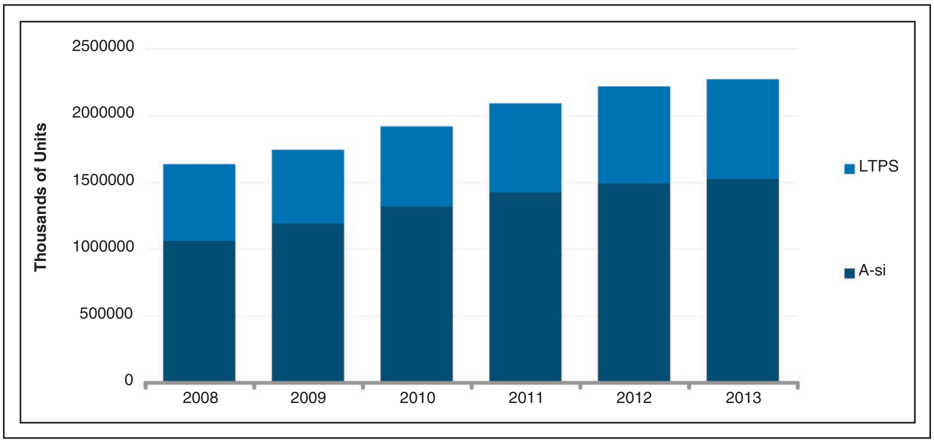

Fig. 2: *Through 2013, LTPS, along with a-Si, is predicted to gain in terms of overall LCD volumes shipped. Source: iSuppli Corp.*

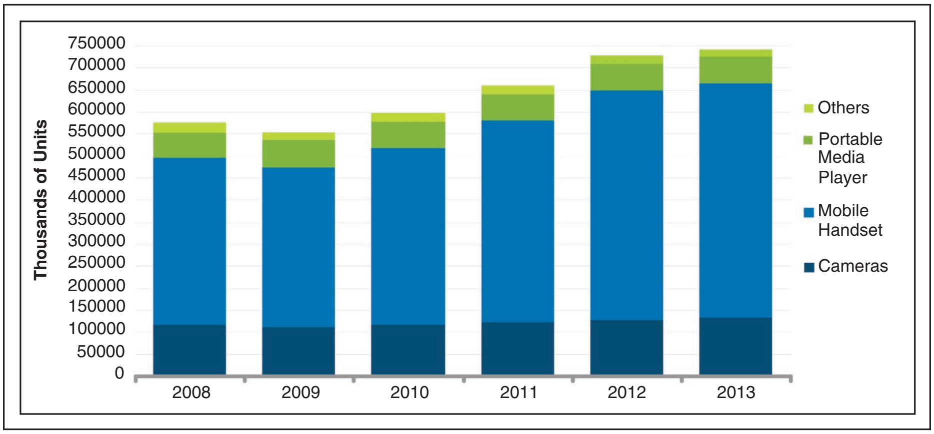

Fig. 3: *The LTPS-LCD shipment market by application shows overall units increasing through 2013, and mobile handsets retaining the lion's share. Source: iSuppli Corp.*

seems to have found its main niche in portable active-matrix devices. These include notebooks, but also mobile phones, smartphones, and cameras (see Fig. 3). "In terms of overall volume for 2009," says Jakhanwal, "mobile phones represent 65%." The other main applications, she continues, are digital cameras (21%) and portable media players (11%).

The mobile-phone application is a logical one, as consumers are requiring devices to display an ever-wider range of content. "The mobile market is really being challenged to provide higher-resolution displays," says Steve Vrablik, Business Development Director, LCDs, with Toshiba America Electronic Components, Inc. As mentioned earlier, LTPS is very suitable for creating high-resolution displays. Vrablik notes that in 2008 TMD created 3.0-in.-diagonal WVGA displays that were used in many mobile phones in the Japanese market, and that this resolution trend is now catching on elsewhere. "This is very, very dense imagery." Not all LTPS displays are diminutive, however. In 2004, TMD came out with a 32-in. panel and currently focuses its larger-size production for notebook display applications in sizes up to 15.4 in.

Drawbacks and Challenges

Although LTPS is highly useful technology, it does not appear poised to take over from a-Si TFTs. One reason for this is that "It is more expensive," says Colegrove, noting that the annealing process is expensive because the lasers themselves are costly, and the process itself takes extra time. And, as in all things, manufacturing, overhauling existing production lines, or creating entirely new fab lines to accommodate a different technology is no small matter. The question of scale comes into play – the more a company can produce, the more it stands to save from making such changes, but it has to have conviction in the long-term viability of the technology.

Toshiba's Vrablik says that TMD has been able to offset expenses incurred by LTPS through garnering savings in component costs. TMD built its AFPD, at the time the world's largest production plant for LTPS TFT-LCDs in Singapore in 2002. And in 2006, it announced plans to invest approximately $270 million in a new production line to produce LTPS LCD panels in its Ishikawa Works in Japan.

What's Ahead for LTPS

As mentioned earlier, another prominent and promising application for LTPS is as a backplane for AMOLED products. "Currently, about 100% of AMOLED products use LTPS," says Colegrove. Samsung is a major player in this area, notes Jakhanwal. In 2007, Samsung SDI introduced a 31-in. OLED panel with an LTPS backplane. In 2008, it showed a 40-in. model at FPD International, and in 2009 demonstrated a 21-in. OLED TV with a 1,000,000:1 contrast ratio.

Where will LTPS be in a few years? Jakhanwal points to its current market share: "LTPS is doing really well," she says. "There's been tremendous growth." Will LTPS eventually wrest the bulk of market share from a-Si? Probably not, according to Colegrove: "We would forecast that it will grow, but it will be limited. LTPS is only about 3% *vs.* a-Si of the total TFT substrate market now and over the next several years." For a technology that might take on a-Si at some point in the future, "Besides LTPS, I would look for some other technology, perhaps oxide-TFT," she says. ■

editorial

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Also this year, LG invested heavily (over US$500 million) in low-temperature polysilicon (LTPS) TFT-LCD production, with the goal of having 20K-sheets/month glass start capacity by 2010. That's a lot of cash to tie up during a recession. Many smaller companies invested in LED-backlight retro-fit systems, and white-LED manufacturers achieved remarkable gains in light efficiency in the same time frame. New investments were also seen in handheld touch screens, overlays, and numerous portable display systems. Large-area LED display technology saw several new innovations, including distributed tiles or "meshes," as they are called, that can be used as distributed building blocks of addressable space. Not a new concept, but a very new embodiment. Finally, this was certainly a year in which OLED technology proved it will be worth waiting for, with heavy spending on commercialization at Samsung and its R&D partners combined with impressive technical announcements and demonstrations at all the major shows.

Countless other examples exist, many of them featured throughout the year in this magazine – proof enough that there are courageous companies are out there. We believe they will be rewarded.

Even more encouraging is the fact that many companies have recently made significant manufacturing investments, including building out new fab lines for LCDs, starting the world's first large-volume lines for OLED displays, making large-scale innovations in LTPS and flexible substrates, and achieving dramatic gains in capacity for eletrophoretic displays. Manufacturing is, of course, the obvious end game for almost all of the development work that we chronicle. A technology that cannot be manufactured in high volume for a reasonable cost rarely gets past the research phase at most companies. Sometimes new developments require new manufacturing methods to be realized, and it is frequently at this last stage where the largest part of the investment gets consumed. In this current economic climate, the fact that these investments are being made at all is a symbol of real courage and leadership.

The final thing I want to talk about this month is mentoring. The late Professor Randy Pausch talked and wrote about enabling dreams; his own and those of his students. It's not enough for each of us to "do;" we also need to be willing to impart our experiences on the next generation. By teaching and mentoring the next generation of engineers. We are enabling their dreams as well as giving them the tools to build the dreams of countless more people in other disciplines. We can't know in advance how each little piece of technology we touch will fit into the giant web of the future, but it is awesome to think that the things we do with displays can create unbelievable leverage for many kinds of growth in the future. From simple televisions came the tools for a whole new type of surgical discipline, as well as the windows for deep-space exploration, and other products that went on to spur the amazing economic developments of whole countries. All of these discoveries came about through the minds of students who were mentored until they became the mentors. Each generation grows on the knowledge of the previous and just a few minutes of your time could lead to an inspiration in someone else that becomes the next great achievement.

So, for the next few weeks, it's OK to have a little bit of "awe" in your work attitude – look at things less analytically and more emotionally. Share that energy and awe with those around you. Teach as you were taught and enable the dreams of as many people as you can!

It's a pleasure to introduce this month's issue focused on manufacturing technology and guest edited by our colleague, industry expert Greg Gibson. Greg has brought us two Frontline Technology features that highlight innovative manufacturing developments involving flexible substrates and I suggest you read his guest editorial first to appreciate the background for both articles and how they represent significant achievements in the flexible substrate space.

In our monthly Display Marketplace feature, Charles Annis and Paul Semenza from DisplaySearch provide us with a very comprehensive survey of the various technologies being employed by LCD manufacturers to improve light transmission, reduce power consumption, and improve manufacturing yields. Taken together, these various techniques, all at some level of commercial implementation today, are driving the next generation of high-efficiency LCD TVs.

This month we also have another installment in our continuing coverage of "green" technology examining the complicated issues surrounding recycling of electronic devices such as TVs and cell phones. There are numerous challenges to both implementing the many growing regulations as well as effectively enforcing them and it has left many manufacturers struggling to find the right balance between commercial interest, environmental responsibility, and limitation of liability.

From the Enabling Technology file comes another homework assignment we gave to Jenny Donelan, this time to report on the state of the art for low-temperature-polysilicon technology. As I mentioned earlier, LG has invested heavily in manufacturing capacity for LTPS and is betting on its unique characteristics to enable advanced display designs for mobile devices. In the mobile-display marketplace (screens 10-in. and less), about 32% are made with LTPS TFTs rather than a-Si. About 65% of all LTPS applications are mobile phones. While this is not a technology poised to skyrocket, because of the expense and difficulty of converting existing production lines, it has its space in enabling small-sized high-resolution LCDs as well as reducing power consumption and footprint.

We also have our regular departments this month, including a message from SID President Paul Drzaic, and some SID news on a recent honor bestowed on Dr David Fyfe and Professor Sir Richard Friend. I hope you enjoy this issue as much as we did assembling it. ■

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The following papers appear in the January 2010 (Vol. 18/1) issue of *JSID*. For a preview of the papers go to sid.org/jsid.html.

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suming to pull them apart. A promising start in this area, according to Allen, are Design for Disassembly initiatives, in which electronics are designed from the beginning to be taken apart quickly and safely. Such design features might include low or no-lead solder, modular electronics boards, and pieces that snap together (or apart) without glue. In most cases, such items would be disassembled by recycling specialists rather than consumers, but the latter alternative is possible as well.

Consumer Caring is Key

The recycling situation as it now stands is a tough challenge not only for the environment but for consumers and manufacturers. Progress has to start somewhere, however, and there are bright spots. First, companies such as Staples have made some headway in developing recycling programs that actually win customer follow-through. The office-supply chain received the Environmental Leadership Award from the National Recycling Coalition this year for initiatives recognized as an industry model. By making it easy for customers to return any brand of ink cartridges at any store, and offering a financial incentive ($3 a cartridge) to do so, the chain has made strides and reports that it is on track to recycle 50 million cartridges in 2009.

As long as bottom-line responsibility for recycling is hard to pinpoint (should it belong to the manufacturer, the waste hauler, the consumer?), the legislation remains difficult to enforce, but in the meantime, public opinion seems to be doing some of the work, both in alerting end users to the importance of recycling and in pointing out which companies are forwarding the cause. The very fact that so many electronic devices are stockpiled in homes and offices indicates that many people are not comfortable just tossing them into a dumpster. “Watchdog” agencies such as Greenpeace also report the names of companies not involved in recycling or not living up to their recycling claims. Greenpeace publishes a monthly ranking of the 18 top manufacturers of personal computers, mobile phones, TVs, and games consoles according to their policies on toxic chemicals, recycling, and climate change (http://www.greenpeace.org/international/campaigns/toxics/electronics/how-the-companies-line-up). None of them get “perfect” scores, but as of September 2009, Nokia, Samsung, and Sony Ericsson received the highest marks.

Time will tell whether such messages will reach beyond those who follow the news from political activists. Like other fundamental consumer behavior changes - consider how Americans began using fewer plastic shopping bags for the first time this year - electronics recycling will be most successful when end users’ awareness and manufacturers’ ability to make it easy for them to act on that awareness meet in the middle somewhere. ■

SID News

Dr. David Fyfe and Professor Sir Richard Friend Awarded the 2009 Institute of Physics Business and Innovation Medal

Dr. David Fyfe, CEO of Cambridge Display Technology and Professor Sir Richard Friend of Cambridge University were awarded the Institute of Physics’ Business and Innovation Medal in October 2009 for “guiding the company Cambridge Display Technology (CDT) to a pre-eminent position in the development of light-emitting polymers and in the development of the technology for flat-panel displays and lighting.” The prize was one of four gold medals awarded annually by the Institute of Physics (IOP) and is for outstanding contributions to the organization or application of physics in an industrial or commercial context.

Fyfe commented, “I am honored to receive and share this award with Sir Richard in recognition of our efforts in developing and commercializing this technology platform. The award is also recognition of the many scientists, investors, and supporters of CDT who have helped drive the technology to its leading position for the future of the displays and lighting markets.”

The discovery that certain polymers can emit light when an electric current is passed through them was made by Jeremy Burroughes (Chief Technology Officer for CDT) under the guidance of Professor Richard Friend with assistance from Professor Donal Bradley at the University of Cambridge in the late 1980s. Realizing the potential for the technology, Friend and colleagues promoted the spinout of the intellectual property into CDT, which was initially funded by the University, as well as various business “angels” and local venture capitalists. Fyfe joined CDT in 2000, leading its expansion from a laboratory-based research company to one that built a manufacturing process development line near Cambridge and entered the manufacture of ink-jet printers in California to enable CDT’s technology to be applied on an industrial scale. ■

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processing, with the potential of producing manufacturing quantities of rugged, flexible, plastic displays as the end product. This issue contains an interesting overview of one such approach to the flexible-display market, “Flexible E-Book Displays Produced in Standard TFT and Module Factories,” by Ian French of PVI.

Free sheet or sheet-to-sheet (S2S) processing is also an emerging manufacturing process for certain applications. This technique uses flexible plastic in cut sheet form that is processed on highly modified (or completely unique) versions of display-manufacturing equipment. Due to the absence of a rigid carrier plate, there are limitations to overlay accuracy and registration using this approach, which will therefore limit the use for high-resolution displays. However, for certain applications, this approach offers unique advantages, such as the absence of a lamination/delamination step and the ability to produce units at very low cost. This approach also allows the use of many of the base technology and existing toolsets that have been developed for “conventional” display manufacturing and avoids the integration challenges of moving completely to R2R production. In “High-Volume Manufacturing of Photonic Components on Flexible Substrates,” Dr. Robbie Charters of RPO provides a detailed description of the implementation of S2S processing for the manufacture of RPO’s digital waveguide devices, which are being commercialized for touch-screen applications.

Flexible-substrate manufacturing, using the carrier plate or sheet-to-sheet approach, could be an important transitional technology for products that are ultimately produced on a roll-to-roll line. Alternately, the unique advantages of these approaches could offer long-term benefits and product characteristics that cannot be realized with any other method. Either way, the end products made possible by these methods should offer a compelling addition to the range of products based on their glass-based display cousins. ■

***Greg Gibson** is Chief Technology Officer for FAS Holdings Group, LLC.*

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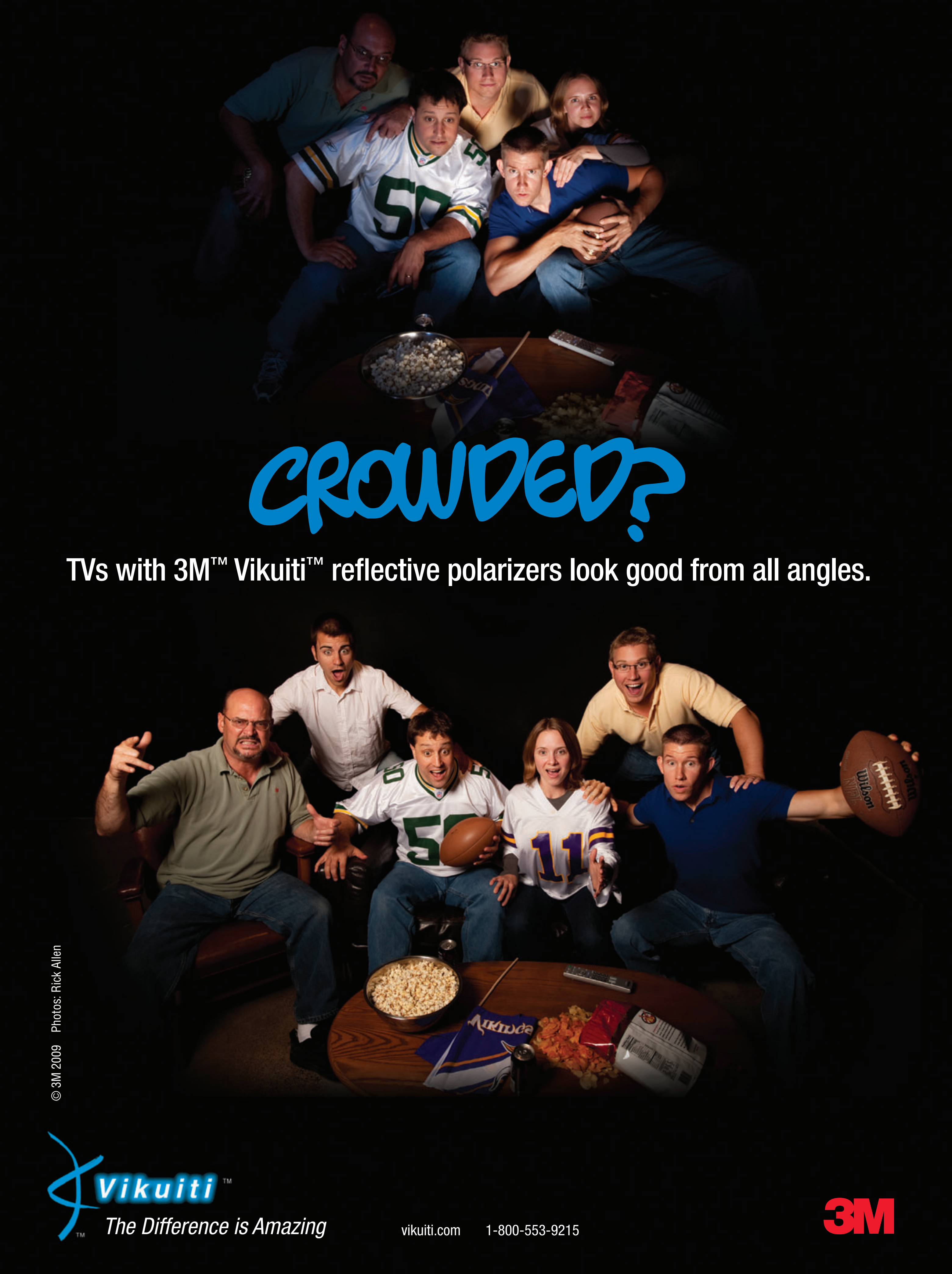
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PROFESSIONAL INFORMATION

1. Are you professionally involved with information displays, display manufacturing equipment/materials, or display applications?

110 ☐ Yes 111 ☐ No

2. What is your principal job function? (check one)

210 ☐ General /Corporate /Financial
211 ☐ Design, Development Engineering
212 ☐ Engineering Systems (Evaluation, OC, Stds.)
213 ☐ Basic Research
214 ☐ Manufacturing /Production
215 ☐ Purchasing /Procurement
216 ☐ Marketing /Sales
217 ☐ Advertising /Public Relations
218 ☐ Consulting
219 ☐ College or University Education
220 ☐ Other *(please be specific)*

____

3. What is the organization's primary end product or service? (check one)

310 ☐ Cathode-ray Tubes
311 ☐ Electroluminescent Displays
312 ☐ Field-emission Displays
313 ☐ Liquid-crystal Displays & Modules
314 ☐ Plasma Display Panels
315 ☐ Displays (Other)
316 ☐ Display Components, Hardware, Subassemblies
317 ☐ Display Manufacturing Equipment, Materials, Services
318 ☐ Printing /Reproduction / Facsimile Equipment
319 ☐ Color Services /Systems
320 ☐ Communications Systems / Equipment
321 ☐ Computer Monitors /Peripherals
322 ☐ Computers
323 ☐ Consulting Services, Technical
324 ☐ Consulting Services, Management /Marketing
325 ☐ Education
326 ☐ Industrial Controls, Systems, Equipment, Robotics
327 ☐ Medical Imaging /Electronic Equipment
328 ☐ Military /Air, Space, Ground Support /Avionics
329 ☐ Navigation & Guidance Equipment /Systems
330 ☐ Oceanography & Support Equipment
331 ☐ Office & Business Machines
332 ☐ Television Systems /Broadcast Equipment
333 ☐ Television Receivers, Consumer Electronics, Appliances
334 ☐ Test, Measurement, & Instrumentation Equipment
335 ☐ Transportation, Commercial Signage
336 ☐ Other *(please be specific)*

____

4. What is your purchasing influence?

410 ☐ I make the final decision.
411 ☐ I strongly influence the final decision.
412 ☐ I specify products/services that we need.
413 ☐ I do not make purchasing decisions.

5. What is your highest degree?

510 ☐ A.A., A.S., or equivalent
511 ☐ B.A., B.S., or equivalent
512 ☐ M.A., M.S., or equivalent
513 ☐ Ph.D. or equivalent

6. What is the subject area of your highest degree?

610 ☐ Electrical /Electronics Engineering
611 ☐ Engineering, other
612 ☐ Computer /Information Science
613 ☐ Chemistry
614 ☐ Materials Science
615 ☐ Physics
616 ☐ Management /Marketing
617 ☐ Other *(please be specific)*

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7. Please check the publications that you receive personally addressed to you by mail (check all that apply):

710 ☐ *EE Times*
711 ☐ *Electronic Design News*
712 ☐ *Solid State Technology*
713 ☐ *Laser Focus World*
714 ☐ *IEEE Spectrum*

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☐ I wish only to receive a **FREE** subscription to *Information Display Magazine* (U.S. subscribers only). Questions at left must be answered.

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