FILMS AND COATINGS ISSUE

Information DISPLAY

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Bringing Displays to Life

THE EVOLUTION AND FUTURE OF OPTICAL FILMS

SOLUTION-COATED AMOLED DISPLAYS

R2R-PROCESSED FULL-COLOR REFLECTIVE DISPLAYS

UNRELENTING DEMAND FOR OPTICAL FILMS

Plus

Journal of the SID
January Contents

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ON THE COVER: *The topic of films and coatings cuts across many of the key building blocks of displays. One of the most interesting and exciting trends is the hybridization of these display technology platforms with non-display applications that will drive the display industry to continue to significantly expand in the coming years by not only continuing to enrich the visual experience of information displays, but also enabling the growth of other key industries with potential for even larger impact on the typical consumer.*

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Next Month in *Information Display*

Flexible and Mobile Displays
- Flexible Universal Plane Technology
- Novel Flexible Displays
- The State of Color
- Outlook and Trends

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editorial

The Pace of Innovation in the New Year

Stephen P. Atwood

Happy New Year and welcome to 2011. It is exciting to begin another year here with *Information Display* magazine. In fact, this issue begins my 6th year as Executive Editor, and I'm very proud to be part of this prestigious publication. Over the past 5 years, we have printed hundreds of articles covering very nearly every conceivable aspect of the display industry, and a great many of these articles have made truly innovative disclosures that you would have been unlikely to learn about from any other media source. This is especially true for leading-edge developments that sometimes take several more years to become commercially prominent.

Each year, we choose our issue themes based on our best assessment of the future direction of the industry and the topics we perceive to be "hot." Some topics, such as LCDs and flexible displays, are perennials that will clearly continue for years to come. Others, such as touch, 3-D, OLEDs, and TV technology, are more recent additions that represent the specific trends of the industry over the last couple of years. Some topics, such as optical metrology or portable displays, have not returned this year. The former is a field that enjoys a small but dedicated following and makes critical contributions to displays. However, there was little new to report this year except for the ongoing important efforts by the ICDM to develop the release of IDMS version 1.0, which we hear will finally make it out of committee in 2011. Portable displays are ubiquitous and have thoroughly fulfilled their promise over the recent years. Industry emphasis has now turned to flexible and ultra-low-power displays, which is why we added this fairly new focus in 2010 and will continue to follow it in 2011.

Which brings us to this month's issue theme: films and coatings. This is a new topic for us, but one that reflects one of the least recognized but most critical components in the supply chain for LCDs and other display technologies. A typical cell-phone display can use as many as six separately engineered films, while commercial televisions may use more than a dozen discrete films and coating components. The vast majority of these components address light management and viewing-angle enhancement requirements, but engineered films can also be used for electromagnetic shielding, surface-durability improvements, and even the integration of touch within the structure of the display.

We were fortunate to have assistance with this issue from guest editor Ion Bita, a staff engineer and manager for the Display Technology Center at Qualcomm MEMS Technologies. With his assistance, we were able to feature articles from some of the most important names in films and coatings, including 3M, Dupont, and HP.

In our first feature article this month, "Getting the Light Through: TFT-LCD Optical Films," author Paul Semenza provides a great survey of the many different types of light-management films in use today to improve the performance of TFT-LCDs. From polarizers to diffusers, prism films, and others, Paul not only gives us the application landscape but also provides a very insightful look at the marketplace for these components as well.

While we're on the subject of light-management films, our next contribution comes from the recognized leader in brightness-enhancement films – 3M. Authors John Schultz and Bret Haldin share with us a number of new film innovations in their article, "Market Evolution and Demand for Thin Films: Projective-Capacitive Touch and

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4G Mobile Network Looms Both Near and Far

In October 2009, *Information Display* published "The Approach of 4G," which looked at what the next generation in mobile networks had to offer and when it would become available. In short, 4G would be fast, as much as 3–5 times faster than what was currently available and would enable all the mobile Internet applications that carriers were sure end users wanted – seamless access to movies, web browsing, *etc*. At the time, consensus among industry experts was that, despite excited pronouncements from carriers, 4G was a long way off. Only about 25% of users were even taking advantage of the previous generation, 3G.

A year and a few months later, even though market penetration of 3G remains at about 25% or just slightly higher,[1] 4G is here – and it is still a long way off. If that sounds confusing, it is. Carriers have begun to roll out 4G service and products. Verizon, for example, launched its 4G network in the U.S. in December 2010, along with at least one 4G-compatible phone, the LG LV600.[2] According to a recent report in *The Wall Street Journal*, 4G in general has been working better than anticipated.[3]

However, many industry pundits are claiming that the current "4G" service is not 4G at all because the ITU (International Telecommunications Union) announced a set of standards for 4G in October 2010 that are not what any carrier is currently capable of – such as download speeds of 100 Mbps.[4] According to a recent article by David Goldman from CNN Money.com, which refers to the 4G phenomenon as a "confusing mess," even the fastest current 4G network is only capable of speeds somewhat over a tenth of 100 Mbps.[5]

However, the term "4G" has been around well before the ITU's recent determination, and U.S. carriers do not seem, at least on the surface, to be concerned with the ITU's standards. It seems that carriers are choosing to view "4G" as "fourth generation" in terms of faster than the last generation rather than a label of specific capabilities. For that reason, and also because the appearance of 4G before 3G has penetrated even a third of the market could conceivably lead to consumer confusion and subsequent buyer paralysis, industry experts predict that the term "4G" may disappear from marketing parlance in the near future. As for now, if you sign up for 4G service, you will not be downloading movies at 100 Mbps, but you will have faster service than you did before.

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— *Jenny Donelan*

guest editorial

Films and Coatings Advance the State of Displays

by Ion Bita

Welcome to 2011, and a Happy New Year to all. We start the year with a look at some of the recent developments in the areas of display films and coating technologies.

In a broad sense, the topic of films and coatings cuts across many of the key building blocks of displays – panel manufacturing, optical enhancement films, components such as touch sensors, and display assembly processes such as lamination and bonding. Many noteworthy developments were reported in all of these areas at the 2010 SID Display Week Symposium, with progress made in materials, processes, device architectures, and applications. One of the most interesting and exciting trends we are seeing is the hybridization of these display technology platforms with non-display applications, such as general lighting and photovoltaics, a result of synergies in large-substrate device manufacturing and light-management solutions. I believe that these synergies will drive the display industry to continue to expand significantly in the coming years, by not only continuing to enrich the visual experience of information displays, but also enabling the growth of other key industries with potential for even larger impact on the typical consumer.

We assembled in this issue a collection of three articles from companies that are leaders in developing display technologies with potential for enabling synergies across multiple industries.

The first contribution is by John Schultz and Bret Haldin from 3M, a company that needs no introduction to the display community, given its long history of achievements in display-enhancement films and materials. Their article, "Market Evolution and Demand for Optical Films," gives a snapshot for developments in the area of display films and touch-sensor technologies. As a highlight, the authors show how the LCD optical-films platform is getting reshaped to enable critical developments in the younger field of 3-D displays that do not require glasses (autostereotopic viewing). A particular type of 3-D enhancement-film solution developed at 3M is described, including a double-sided patterned film with a microlens array on the side of a directional backlight unit and a microprismatic array on the LCD-panel size that is registered to the other surface with micron-level tolerances. An important feature of this innovative solution is that the microlens film does not need precise alignment with the LCD pixels or light-guide features, simplifying module assembly at the OEMs.

The next article is by Jong-Souk Yeo, Tim Koch, *et al.* from Hewlett-Packard, reporting on impressive progress in flexible-display fabrication and architectures in "Paper-Like Electronic Media: The Case for R2R-Processed Full-Color Reflective Displays." This article showcases a comprehensive approach towards developing a novel reflective display technology – an electrokinetic pixel technology based on electrochromic coatings stacked for full-color operation, development of transparent metal-oxide TFTs, and a roll-to-roll (R2R) processing platform for flexible plastic substrate fabrication based on the self-aligned imprint lithography process developed at HP. This unique combination of a color-display technology in a plastic R2R-fabricated active-matrix backplane is discussed as enabling a scalable platform for low-power transparent print-like media and a path towards eco-friendly bright full-color flexible electronic media that can be extended to new markets such as digital signage.

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Getting the Light Through: TFT-LCD Optical Films*

The demand on TFT-LCDs to create bright high-resolution full-color images in a thin package and at low power levels has been unrelenting. This engineering challenge would not be possible without the use of optical films to collect, direct, filter, and otherwise "manage" the light through the display. Growing demand for "green" LCD panels, the use of LED backlights, and new power-consumption regulations are driving new backlight designs to add more optical films, creating opportunities for filmmakers who can provide improved technology.

by Paul Semenza

TFT-LCD PANELS are built from several components, including glass substrates, liquid-crystal mixtures, coatings, frames, and optical films. These films play an important role in the TFT-LCD module in aiding the control, diffusion, and management of light to improve viewing angle, contrast ratio, and other performance metrics.

Components of the Display Optical Stack

TFT-LCD optical films include polarizers, which linearly polarize the light into and out of the LCD panel, and backlight optical films, which are films or sheets that improve optical efficiency, recycle light in the backlight system, or diffuse brightness for uniformity. Backlight optical-film types include normal and multi-functional prism sheets as well as micro-lens, reflective polarizer, diffuser, and reflector films (Fig. 1). While two polarizers are always used, all of the other films can be used in varying quantities, or not at all, depending on the panel design, which, in turn, depends on screen size and application, cost, physical design, and power-consumption requirements.

Polarizers

TFT-LCD polarizers are themselves composed of different films (Fig. 2). Triacetyl cellulose (TAC) is an encapsulation film used to support and protect the (polyvinyl alcohol (PVA) layer that performs the polarization.

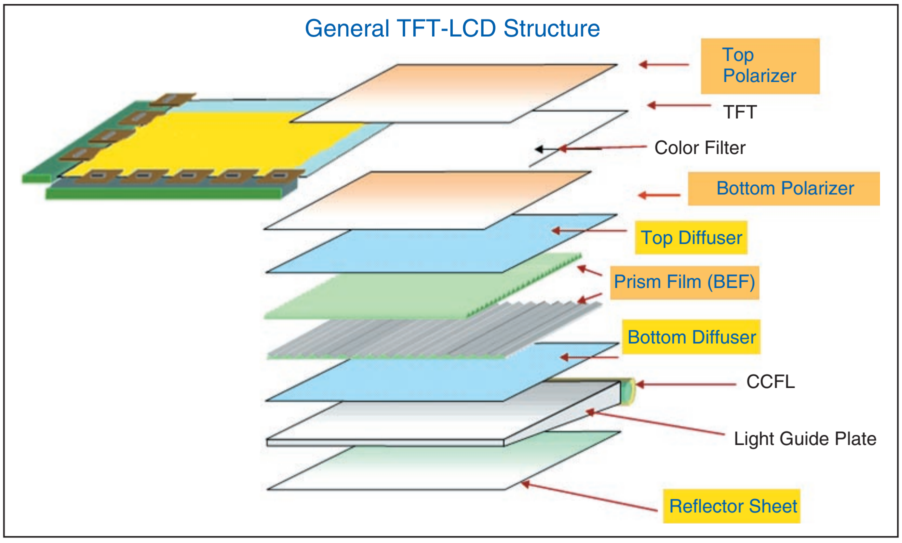

***Fig. 1:** There are several different types of films used in TFT-LCD panels, including the ones used around the LC cell, within the backlight, and between the backlight and the cell.*

*This article is based on DisplaySearch's *Quarterly Display Optical Film Report.*

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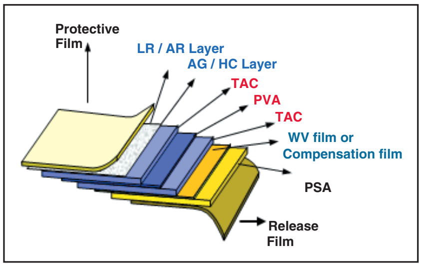

Fig. 2: Polarizers are multi-layered films combining structural, polarizing, and light-management functions.

The requirements for TAC are high light transmittance, low retardation, low color shift, high adhesion to PVA, and ease of manufacturing. Compensation films correct for the phase-retardation property of liquid crystals, which otherwise can result in contrast-ratio reduction, gray-scale inversion, and color shift at particular viewing angles. Surface treatment improves visibility and prevents loss of contrast due to reflection. Typical treatments include anti-glare, low reflection, anti-reflection, hard coating, and anti-static.

Prism Sheets – Multi-Function Prism Films

Prism film, also called lens film or prism sheet, contains micro-replicated prism structures on polyester (PET) or polycarbonate (PC) film. Prism sheets are used in the LCD backlight module to enhance luminance by directing off-axis light from the light source through the prism structure. A single sheet of prism film can direct light toward the viewer in the horizontal or vertical plane only; off-angle light in the other plane is not affected. However, by stacking two prism films – one for the horizontal off-axis light and one for the vertical off-axis light – on top of each other, a two-dimensional optical system can be achieved.

Brightness-enhancement film (BEF) is the marketing name for prism film used by 3M. It is the dominant prism film, but is being challenged from several directions. First, some of the basic patent protection held by 3M on its BEF product is expiring, opening the door to competitors. Also, in notebook PCs, an alternative technology has emerged that marries a reverse prism film with a prism-functioning backlight to replace the two stacked prism sheets. Another emerging trend involves micro-lens or diffuser films, which combine diffuser and prism functions in one film (Fig. 3). As backlight brightness increases and cell transmittance improves, micro-lens film can replace conventional prism film or reflective polarizers, thereby reducing cost.

	Prism Film	High Gain Diffuser/Micro Lens	Conventional Diffuser
Anti-scratch	Poor	Fair	Good
Optical gain (on-axis)	1.6/one sheet 2.2/two sheet	~1.3/one sheet 1.5/two sheet	1.1/one sheet 1.3/two sheet
Major Function	Light collection/ enhancement	Light collection + diffuser	Diffusing
Cost	High	Middle	Low
Optical Mechanics	TIR + Refraction	Refraction + scattering	Scattering

Fig. 3: Micro-lens film combines the functions of both prism-film and diffuser sheets, providing an optical gain in between that for these two sheets, and potentially reducing cost.

A further development is lenticular films, which have a lens arrays with rounded vertices and curved surface profiles and simultaneously exhibit light convergence and diffusion (Fig. 4). These films do not require protective films, do not suffer heat-induced waving in the luminance profile, and are easy to handle in the assembly process. Lenticular-type films offer 3–8% higher brightness (from dual collimation and higher lens density) than micro-lens film, as well as lower cost.

Reflective Polarizers

Reflective polarizers recycle light from the backlight system that would be absorbed by the LCD and can increase brightness by 50–60%. These films select incident light with a specific polarization state to pass through and reflect the other polarization state back into the backlight where it can be recycled; they are used in TFT-LCD products requiring high brightness, such as TVs, high-end notebook PCs, and high-end monitors. There are different approaches to making reflective polarizers: the most common are multi-layered polarizers, which have hundreds of layers that are less than 100 nm thick, and constructions consisting of cholesteric liquid crystal and wire grids.

3M has strong IP and technical positions in multi-layered reflective polarizers, which it markets as dual-brightness-enhancement film (DBEF), but several panel makers are starting to seek alternative solutions. The TFT-LCD reflective-polarizer market grew rapidly over the past year, due to the need for green design,

	Prism sheet	Lenticular	Microlens
Basic texture	Right angle	Curved profile	Spherical lens
Distribution	Linear	Linear	
Optical Function	Light concentration	1D concentration + diffusing	2D concentration + diffusing
Module Function	Light enhancement	Lamp mura reduction	High gain diffusing
Optical Gain	~1.6x	~1.5x	~1.3x
Assembly yield	Low	Fair	Good
IP issue	High	Low	Low
Cost	High	Fair	Low

Fig. 4: Prism-sheet and multifunction-film technologies are compared.

the use of LED backlights, and the trend toward reduced power consumption. However, increasing panel transmittance and LED luminance will impact the usage of DBEF.

Diffusers

Diffusers spread and randomize the light across the display to minimize brightness variations. In the most common type of diffuser plate, acrylic beads are spread in a resin layer, creating a medium whose refractive index varies with location; when light passes through this layer, the beads cause refractions, reflections, and scattering that lead to the overall optical-diffusion effect. Micro-lens arrays are also being used, and hologram and engineered approaches are in development (Fig. 5).

Reflectors

There are two types of reflector film: the most common are backlight reflectors (also called "white" or "silver" reflectors), which reflect and recycle light from the light-guide plate, and lamp reflectors, which reflect and recycle light inside the lamp cover. White reflectors are typically about 200 µm thick and have a reflection ratio of about 95%. The reflector film is made of PET. A UV coating is typically used on the surface of the reflector to limit color change. There is also a layer on the bottom of the reflector to increase reflection from the bottom surface. White PET, which is the base material for reflectors, is in shortage due to strong demand from photovoltaic modules. The global capacity for white PET is approximately 4k tons/month, and PV manufacturing is consuming about 1.5k tons/month. PET makers generally find that the PV business is more profitable than displays. With the tight supply, some PET suppliers have raised prices, and some backlight units have adopted transparent PET.

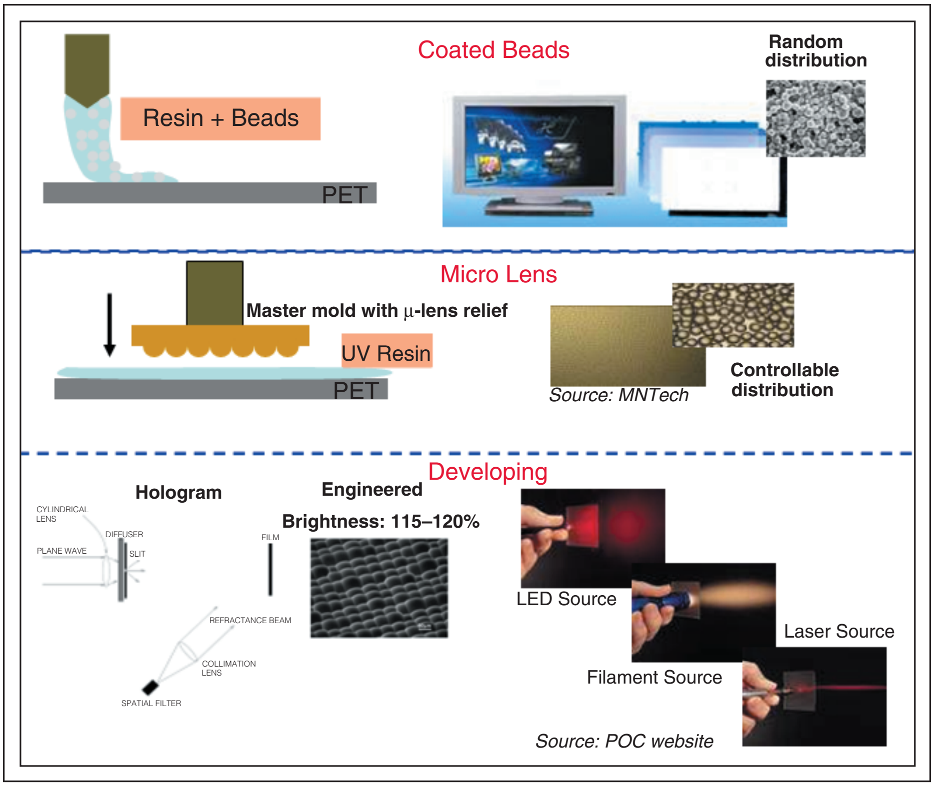

Fig. 5: Coated beads in resin are the most common approach to manufacturing diffusers, but other approaches that could result in improved performance are in production or development.

Wide Variation in Film Stacks

Film stacks can vary widely, depending on requirements including cost, brightness, power consumption, thickness, and type and brightness of the backlight used. In order to maintain brightness with high energy efficiency for notebook panels, two cross-stacked prism sheets are necessary. Therefore, a stack of four films (upper diffuser plus cross prisms plus lower diffuser) is still the mainstream in notebook backlight units (BLUs) (Table 1). In order to reduce cost, the upper diffuser can

Table 1: Film stacks for notebook (12–17 in.) and monitor (15–24 in.) panels

Notebook	Notebook	Notebook	Monitor	Monitor	Monitor	Monitor	Monitor	Monitor
Top diffuser	DBEF	Multi-function prism	Top diffuser	DBEF	Micro-lens film		Top diffuser	
Cross prism sheet x2	Cross prism sheet x2	Down prism sheet	Prism sheet	Prism sheet	Micro-lens film	Multi-function prism	Prism sheet	Lenticular film
Down diffuser	Down diffuser	Down diffuser	Down diffuser	Down diffuser	Down diffuser	Down diffuser	Micro-lens film	Micro-lens film
Light-guide plate	Light-guide plate	Light-guide plate	Light-guide plate	Light-guide plate	Light-guide plate	Light-guide plate	Light-guide plate	Light-guide plate
Reflector	Reflector	Reflector	Reflector	Reflector	Reflector	Reflector	Reflector	Reflector

be replaced by a prism sheet with a haze function (back coating or modified texture) and a conventional prism. Monitors typically use a three-film stack (upper diffuser plus prism plus lower diffuser). Korean panel makers have widely adopted two-film stacks (multifunction prism plus lower diffuser).

Film stacks in LCD-TV BLUs are highly dynamic and diverse, evolving every few quarters. Various optical films are available to LCD-TV BLU makers, and there is more design freedom to find the most cost-effective film stack that meets specifications (Tables 2 and 3). Lenticular films, with performance between that of micro-lens and prism-sheet varieties, are used to reduce the number of cold-cathode fluorescent lamps (CCFLs) and are used with edge-lit LED BLUs to replace the prism sheets (Table 4).

As the number of LED chips used in edge-lit LED BLUs decreases, cross-type prism sheets (horizontal and vertical) are being used to maintain brightness. However, this typically results in a narrow viewing angle. The heat from the LEDs creates difficulties for reflectors and light-guide plates (LGPs), including warping. To provide stiffness and resist bending at high temperatures, thicker optical films are used.

Market Trends in Optical Films

Demand for all TFT-LCD optical films is expected to grow from 567 million square meters in 2009 to 700 million square meters in 2010. However, due to price declines, TFT-LCD optical-film revenues are expected to grow more slowly, from \$9.3 to \$10.5 billion (Table 5). Increased demand in total display area is leading polarizer and backlight films to grow by more than 25% in area in 2010. But while polarizer revenues will benefit from LCD TV, resulting in 16% growth in 2010, backlight films are facing price pressure and are expected to grow by less than 5%.

The supply of polarizers was tight in 2009 and early 2010; some makers had production issues and some makers closed fabs. However, the top five polarizer makers have been expanding capacity, which will ease the tight supply. The supply of polarizers can be limited by shortages of key materials such as PET films used as protection and release films. Unyielded TFT-LCD polarizer capacity is expected to increase by 23% to 463 million square meters in 2010. Nitto Denko and LG Chemical increased production line speed, and Sumitomo, Samsung Cheil, BMC, and CMI are expanding capacity. LG Chemical leads polarizer shipments in terms of both units and area, followed by Sumitomo in units due to strong notebook penetration and Nitto Denko in terms of area due to higher shipments of LCD TVs.

Prism-sheet revenue is expected to increase 4% in 2010 because LED models use more prism and lenticular film. However, the lenticular-film price is lower than that of prism film; therefore, the revenue growth rate is lower than the unit growth rate. Prism-film revenue is likely to drop after 2010.

Table 2: Film stacks for LCD-TV panels, 26–32 in.

			DBEF			Micro-lens film	DBEF	Top diffuser		DBEF
		DBEF	Prism sheet	Multi-function prism		Lenticular film	Prism sheet	Prism sheet		
Micro-lens film x2	Down diffuser x2	Micro-lens film x2	Down diffuser	Micro-lens film x2	Micro-lens film x3	Micro-lens film	Lenticular film	Down diffuser	Lenticular film x2	Microlens film x2
Textured diffuser plate	Textured diffuser plate	Textured diffuser plate	Diffuser plate	Diffuser plate	Diffuser plate	Textured diffuser plate	Textured diffuser plate	Diffuser plate	Diffuser plate	Diffuser plate
U-CCFL	U-CCFL	U-CCFL	CCFL	CCFL	CCFL	CCFL	U-CCFL	U-CCFL	CCFL	CCFL

Table 3: Film stacks for LCD-TV panels, 40–47 in.

Top diffuser		DBEF		Top diffuser		Micro-lens film			
Prism sheet	Lenticular film x2	Prism sheet	Micro-lens film x2	Prism sheet	Multi-function prism	Lenticular film	Prism sheet		DBEF
Micro-lens film	Down diffuser	Lenticular film	Down diffuser	Micro-lens film	Micro-lens film x2	Micro-lens film	Micro-lens film x2	Down diffuser x3	Micro-lens film x2
Diffuser plate	Diffuser plate	Diffuser plate	Diffuser plate	Diffuser plate	Diffuser plate	Diffuser plate	Diffuser plate	Diffuser plate	Diffuser plate
U-CCFL	CCFL	CCFL	CCFL	CCFL	CCFL	CCFL	CCFL	CCFL	CCFL

Table 4: Film stacks for LED-backlit LCD-TV panels, 40–47 in.

			DBEF		DBEF
	Lenticular film		Prism sheet		Prism sheet HxV
	Micro-lens film x2		Down diffuser		Down diffuser
LED	Light-guide plate	LED	Light-guide plate	LED	Light-guide plate
	Reflector		Reflector		Reflector

Table 5: Optical films shipments and revenues

Film	Type	Shipments 2010, Mm^2	Shipments 2009, Mm^2	Revenues 2009, \$M	Revenues 2010, \$M
Polarizer Films		198.3	252.0	$6,468	$7,507
Backlight Films	Normal Prism	62.0	79.5	$806	$835
	Multi-Function Prism	11.2	12.7	$182	$176
	Micro-Lens	49.5	47.7	$304	$245
	Reflective Polarizer	19.7	27.0	$672	$848
	Diffuser	129.9	158.6	$481	$503
	Reflector	96.5	122.1	$356	$430
	Sub-Total	368.8	447.7	$2,801	$3,037
Total		567.1	699.7	$9,269	$10,544

Source: DisplaySearch *Quarterly Display Optical Film Report.*

After growing very rapidly in 2008, the trend toward using multi-function prism film for monitors, the dominant large-area application, slowed in 2009. Part of the reason is due to low-yield issues at BLU makers, and another is that LED models will use normal prism film for better brightness enhancement. Prism film with reflective polarizer functionality is widely used in portable applications, providing better brightness enhancement.

Micro-lens-film revenues are expected to fall in 2010 due to the reduction in the number of lamps used and LED models using a back prism and lenticular structure for increased optical performance. Large-sized TV panels (37 in. and larger) are the dominant application.

The reflective-polarizer market, where TV is the dominant application, grew in 2009 and 2010 due to the expansion in green designs, LED models, and low-power trends. Increasing panel transmittance and LED luminance will impact the usage of DBEF models after 2011.

Reflector-film demand is growing along with large-area demand, and increased performance requirements are keeping prices high. Also, the rapid growth of demand in the solar-cell industry has caused tight supply conditions.

Diffuser demand continues to grow with area, but multi-function prism film includes the top diffuser function and will reduce the usage of diffusers. In the meantime, some lenticular films used in LCD TVs do not require diffusers.

Looking Forward

Polarizers are essential for LCD panels, especially in wide-viewing-angle applications, while films that improve the luminance of the backlight and the LCD module are very important for cost reduction and green panel design; both grow with panel demand. However, cost pressure in the optical-film market is limiting revenue growth. As this trend is likely to continue for the next few years, making technical improvements to reduce production and materials cost is the most critical focus for polarizer and backlight optical-film suppliers. Especially for LCD TV, where power consumption is a major focus of set design, panel makers need to reduce the number of lamps and LEDs that use prism sheets to maintain brightness. Prism sheets are gradually becoming a requirement in LCD-TV panels, which will support increases in prism-film average price and help to reverse the revenue decline. ■

LCD TVs with 3M Film Use Up to 37% Less Power.

3M's Vikuiti™ Dual Brightness Enhancement Film (DBEF)—the world's first reflective polarizer—recycles light that's normally wasted in LCD devices. Adding Vikuiti DBEF can improve the efficiency of LCD TV backlights by 32–52% and can cut total TV energy use by 23–37%. A typical 46″ LCD TV with Vikuiti DBEF and two diffusers, for example, can operate on *83 fewer watts* than the same TV with three diffusers and no Vikuiti DBEF. Feel the joy—go to 3M.com/displayfilms for more information about saving energy with 3M Display Films.

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Market Evolution and Demand for Optical Films

Over the years, thin films have contributed greatly to the evolution of LCD technology. With the current demand for 3-D and projective-capacitive touch, they continue to do so.

by John Schultz and Bret Haldin

SUPPLIERS have made phenomenal leaps in advancing materials so that electronics manufacturers can keep up with and, in some instances, surpass consumers' demands. Two such areas include the role of thin films in the evolution of LCD technology and the function of EMI management in optimizing performance as a result of the rapid growth in projective-capacitive (pro-cap) touch. This article will explore how these separate but interrelated aspects affect display design.

Evolution of LCD Technology

In the short, meteoric rise of liquid-crystal displays (LCDs), few technologies have had the impact-per-ounce that optical films have had. Early in the development of LCDs, these very thin polymeric sheets were able to increase light efficiency, thereby extending battery life so that laptops and other mobile displays became practical. Today, that same film-enabled efficiency means that carefully designed large-format televisions and monitors can become an acceptable choice for energy-conscious consumers. Optical films have also allowed the introduction of stunning new functional capabilities such as 3-D and touch sensitivity. As consumers have demanded sleeker and smaller devices, optical films have also enhanced both performance [by managing electromagnetic interference (EMI)] and the viewing experience. In addition, films provide viewing privacy and protect display surfaces from the assaults of everyday use – from car keys rubbing across a smartphone screen inside a purse to windblown sand striking your tablet as you read at the beach.

The contribution of films will continue for the foreseeable future. Work currently under way promises to give LCDs even greater functionality, better energy efficiency, and greater design flexibility. Autostereoscopic and EMI films, in particular, are illustrative of the recent past and future potential of thin films in LCD technology.

Autostereoscopic Films

Three-dimensional perception provides a level of sheer wonderment in viewers that is rivaled by few other advances in display technology. This has been true since the first full-length 3-D motion pictures were introduced in the last century and has become especially so with the advent of the latest generation of technologies, which include active-shutter and passive glasses. With regard to no-glasses (autostereoscopic) viewing, which is still under development for many commercial applications, the leading technologies are parallax barrier, lenticular, and directional backlight.

Films play a key role – indeed, an enabling role – in several of these technologies and particularly in the directional backlight solution. Recent advances in films for 3-D autostereoscopic displays demonstrate that, in combination with other technologies, such films can be instrumental in achieving the Holy Grail of handheld 3-D displays: "at-a-glance" 3-D perception on-axis along with clear off-axis 2-D perception, full-color fidelity, and full resolution – all without the use of glasses, which are generally unacceptable for mobile device use. (Off-axis 2-D means there is no risk of view reversal, as in parallax barrier or lenticular solutions.)

The key elements of one such possible system design are a 120-Hz LCD panel, a directional backlight unit (DBLU), and a specialized 3-D enhancement film. A schematic cross-section of this configuration is shown in Fig. 1.

The DBLU includes a set of fast-response LEDs on the left and right side, which alternate off and on (with a brief dark interlude). When the left LEDs are lit, the unique shape of the film directs the left image to the left eye; when the right LEDs are lit, the film directs the right image to the right eye. This approach also incorporates a light guide and a reflective film below the light guide, a configuration that is similar to backlights in conventional mobile devices, although the light guide is designed with specific modifications that enable the 3-D enhancement film to achieve its highest performance

It is worth mentioning that the reflective film behind the light guide is an example of the early influence of film technology on

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LCDs. These films' high reflectivity and light weight – the result of hundreds of layers stacked into the thickness of a sandwich bag – were among the keys to the development of laptops and other mobile devices.

3-D enhancement film sets this display apart from other LCDs. It incorporates an innovative film design and a high degree of precision in film manufacturing, unlike other autostereoscopic designs; however, it does not require a precise alignment with LCD pixels or the light-guide features, which means it is easy to integrate into OEM systems.

To achieve its 3-D effect, the film uses lenticular features on the top surface and prism structures on the bottom surface, a design that has been informally dubbed "the ice cream cone," as shown in Fig. 2.

The top and bottom lenticular and prismatic features must be registered with micron-scale tolerances during manufacturing, and the exact size of the features can be adjusted to minimize moiré with the LCD. To provide autostereoscopic 3-D over a large display, the prism pitch is slightly larger than the lenticular pitch so that over the width of the panel the offset between each lenticular/prism pair increases with distance from the center of the display. This offset is a design parameter based on the desired viewing distance and the size of the panel. For example, the 3-D enhancement film shown in Fig. 2 has a 44.000-mm pitch per 1000 lenticular features and a 44.008-mm pitch per 1000 prismatic features; this difference in pitch produces an optimal viewing distance of 400 mm, although 3-D can be seen both closer and farther from the display.

The example in Fig. 2 introduces the latest refinement in 3-D enhancement films: in earlier generations, the prism structures butted directly against each other on the bottom surface; in this iteration, a flat region is introduced between prisms. This flat feature increases film reliability by reducing the tendency for stress fractures to form at the sharp inner groove. Cosmetic features of the film are also improved with the elimination of sharp peaks on the master tooling. Functional testing found no change in the light-output distribution when the flat regions were introduced between prisms.

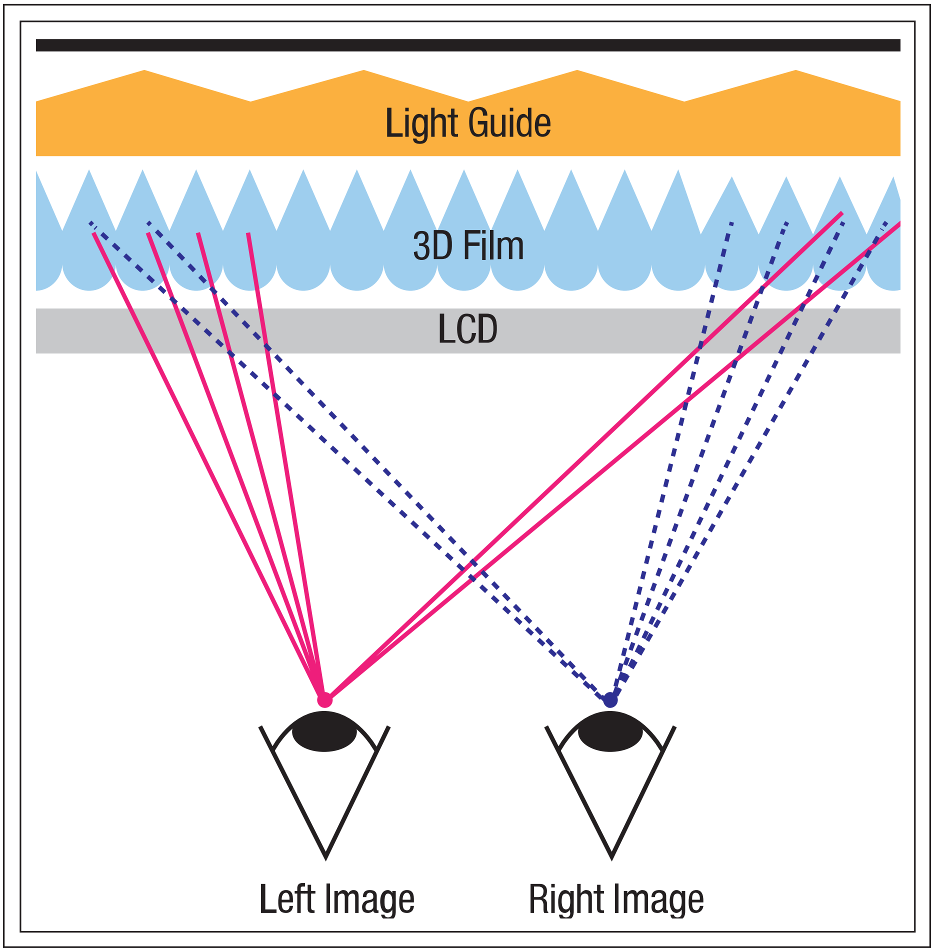

Fig. 1: This autostereoscopic 3-D display uses a directional backlighting unit or DBLU. (Image is conceptual and not to scale.)

Removing Barriers to Adoption

The integration of DBLUs and 3-D enhancement film resolves several of the barriers to a broader adoption of 3-D displays in handheld devices. Among those barriers are the aforementioned glasses. Another is viewer fatigue. There are multiple causes of this discomfort, but one frequent explanation is "reversed viewing" of images that are perceived when the viewer moves slightly off-axis while looking at autostereoscopic devices based on the parallax-barrier and lenticular-lens approaches. The DBLU 3-D enhancement-film approach is autostereoscopic 3-D on-axis and provides clear 2-D viewing when the viewer moves slightly off-axis. This approach also minimizes the "black bands" that can arise between left and right images with autostereoscopic systems.

As autostereoscopic films and their DBLU and fast LCD system components continue to evolve, the limitations of earlier generations of autostereoscopic displays are being resolved. The reduction of cross-talk and the elimination of image reversal − the disconcerting in-out or out-in of images and the "scratchy" visual appearance because of the half-resolution display quality – are good examples of how films and other system components can help break down barriers to adoption. The combination of a 120-Hz LCD panel, the DBLU, and the 3-D enhancement film with appropriate selection of the LED sequencing relative to the LCD panel refresh rate has been effective at reducing cross-talk to visually acceptable levels in a full-resolution autostereoscopic display with at-a-glance viewing.

EMI Films and Touch Technology

Whether for entertainment, information, or work, consumers can not seem to get enough of smartphones, tablet computers, and other types of hand-held devices. State-of-the-art materials are needed to manage the electromagnetic interference (EMI) and touch-sensor performance issues that can arise in these designs, while simultaneously enabling display engineers to keep up with five important trends:

- The rapidly increasing market penetration of projective-capacitive touch.
- Desire for devices that are increasingly thinner and lighter.
- Desire for increased functionality and capability in portable devices.
- Increased interest in larger display sizes for portable devices.
- Demand for state-of-the-art touch functionality

The above-mentioned demand has driven tremendous growth in the area of pro-cap touch sensing in particular. Pro-cap touch displays are currently incorporated into a significant portion of smartphones and are being integrated to support touch capability in larger devices, such as tablets and slates, as well. Pro-cap capability supports single- and multi-touch functionality that as a system integrates relatively well into the current form factors of interest for portable electronic devices.

However, along with these desirable attributes, display engineers and product designers interested in pro-cap systems for their devices face many integration challenges. The system's performance can be impacted by a number of issues, such as sensor design and composition, touch integrated-circuit (IC) capabilities, display characteristics, thickness of the optical stack and cover lens, and the presence or lack of an air gap between the pro-cap sensor and the display. In addition, the demand for multiple functionalities such as GPS, Bluetooth, and Wi-Fi, and the need for their associated antennas, can cause an increased amount of electromagnetic radiation to be present in and around consumer-electronic devices. It is important to note that this radiation, in this case potentially coming from within the device itself, can directly impact that same device's projected pro-cap touch-system performance.

In short, it is not easy to design and tune a pro-cap system for a portable electronic device, and there are many factors, such as the drive toward thinner devices with increased functionality and the demand for larger display sizes, that affect the overall system performance and associated level of touch capability. The combination of the above trends is causing significant focus on the area of EMI management. As alluded to above, pro-cap systems, due to their proximity to radiating surfaces within the device, and their use in a wide range of settings, can often be degraded due to EMI-related issues. These systems rely on the ability of a signal-processing algorithm to detect small changes in capacitance in a conductive circuit, and these changes can be masked by interference from surrounding electronic noise, either from outside the device or from the device's own display.

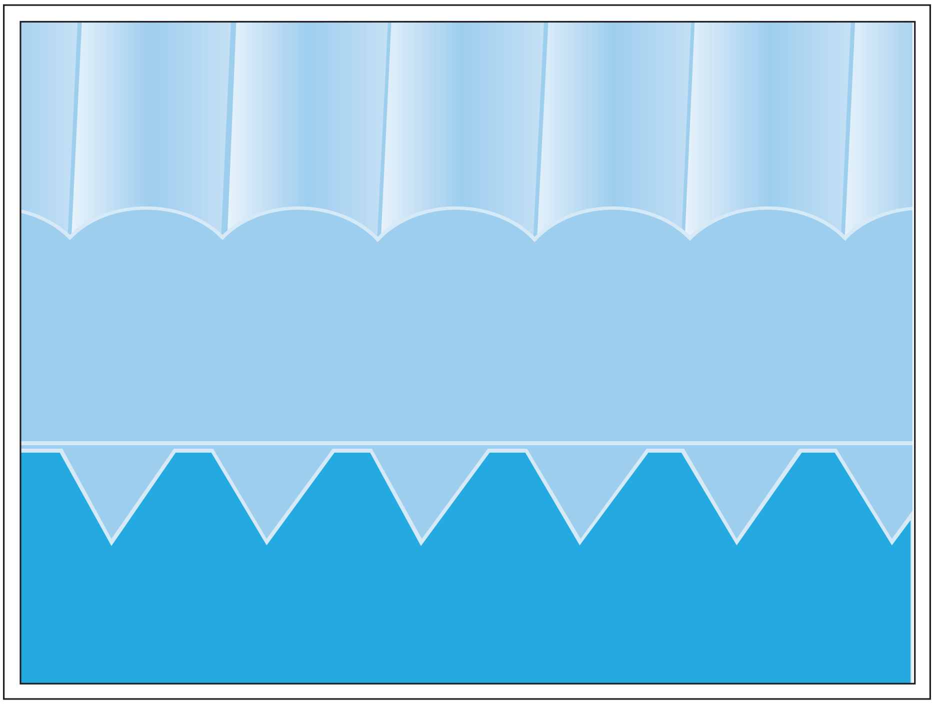

Fig. 2: The signature "ice cream cone" profile of 3M's 3-D film is apparent in this cross-section. This film features prism structures separated by a flat region that improves the film's cosmetic quality.

Materials designed to meet these challenges today are typically constructed using a base substrate such as polyethylene terephthalate (PET) ranging in thickness from 25 to nearly 200 µm, and a thin conductive layer that has either been coated or deposited on the substrate's surface. The conductive layer can be made of materials such as carbon nanotubes (CNTs), high-aspect-ratio structures such as silver nanowires, transparent conductive oxides such as indium tin oxide (ITO) or zinc oxide (ZnO), or conductive polymers such as poly 3,4-ethylenedioxylthiophene (PEDOT). All of these materials seek to minimize the inherent tradeoff that occurs with a transparent conductive material between optical quality – measured by criteria such as photopic transmission, haze, and color bias – and electrical conductivity. Figure 3 illustrates how these materials can be applied with a display stack construction, usually in conjunction with an optically clear adhesive (OCA), to minimize the impact of display-generated EMI on the performance of a pro-cap touch sensor.

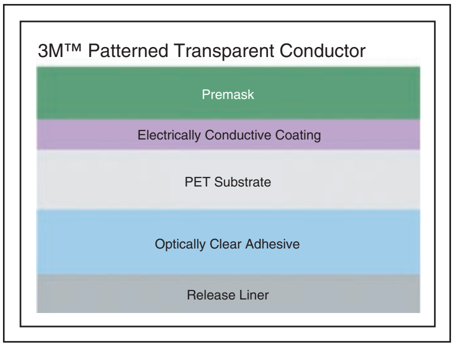

Fig. 3: Film materials can be applied in a display stack construction.

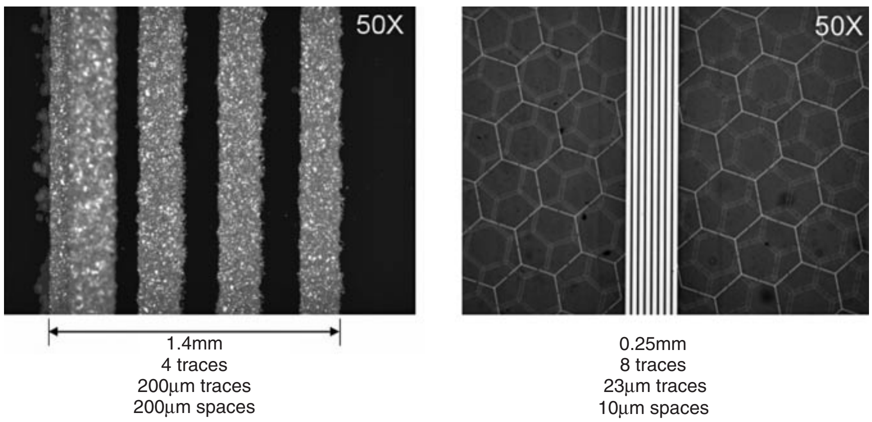

Fig. 4: *On the left are micrographs at 50× magnification of a screen-printed interconnect structure and, at right, a 3M Patterned Transparent Conductor interconnect design for a pro-cap touch sensor.*

There continues to be strong interest in the industry to reduce the width of or even eliminate the bezel around the display, and material suppliers are working to improve pro-cap touch sensors, particularly those on a film substrate, so their interconnects are as narrow as possible. 3M's Patterned Transparent Conductors (PTC) offer high-level performance in this area by utilizing a highly controllable patterning process to provide interconnect structures five to six times narrower than the industry norm. More specifically, PTC offers superior transparency, at resistances that are orders of magnitude lower than existing ITO products, on a polyester film substrate that is highly flexible. These benefits are based on the use of silver conductive traces that are 2–3 µm in width, configured in specific geometries to minimize the optical/electrical tradeoff. These materials offer excellent optics down to sheet resistances lower than 20 Ω/□

In Fig. 4, the narrow-bezel benefit of PTC is illustrated by comparing the screen-printed interconnect structure used in many ITO/PET pro-cap touch sensor designs with a PTC-based interconnect design. The structure at left in the figure measures 1.4 mm in width, while the structure at right is 250 µm across. It is worth noting that the interconnect structure on the left supports a 3-in. display size, while the PTC interconnect structure is for a 4.8-in. display. Despite having a higher number of interconnects, the PTC-based structure is almost six times narrower than the screen-printed design.

Films and the Future of Display Design

Autostereoscopic and EMI-management films have done much to advance the performance and design of LCDs and, in turn, that of today's most popular consumer mobile devices, and they will continue to expand the potential of these devices. However, while using state-of-the-art materials is important, the most successful breakthroughs and designs that can move ahead of the trends will come through early collaboration between internal product design and engineering teams and their material suppliers. It is at this point that engineers will find these materials most valuable, as they continue to tackle the challenges presented by a fast-paced and ever-demanding market.

The films discussed in this article are but two examples of a new generation of films. Other new and transformational films, soon to be introduced, will remove long-standing barriers to improvements in the cost, performance, weight, thickness, and environmental profile of displays. Now more than ever, there are a number of diverse material sets for display engineers to consider that can meet a wide range of design goals while improving and optimizing performance. ■

Paper-Like Electronic Media: The Case for R2R-Processed Full-Color Reflective Displays

A reflective electronic medium with properties similar to printed paper has been a goal within the display industry for many years. Most current reflective technologies use techniques similar to emissive displays to achieve color capability. This article focuses on a design that mimics color printing methods to achieve a wide color gamut and uses a roll-to-roll processing method.

by Jong-Souk Yeo, Richard Elder, Warren Jackson, Randy Hoffman, Dick Henze, and Tim Koch

REFLECTIVE DISPLAYS have seen tremendous growth in recent years, from electronic readers to digital signage. One of the most sought-after additions to this technology has been color. Hewlett-Packard (HP) is approaching the challenge of generating bright high-quality reflective color images from the perspective of printing by layering subtractive colorants (CYM or CMYK) at every addressable pixel location. Layered colorants in electronic media can be enabled by stacking electro-optic layers that are modulated between colored and transparent optical states. And we have developed a novel electrokinetic frontplane architecture that provides a transparent state with electrically addressable colorants and is fabricated on a plastic substrate using roll-to-roll (R2R) manufacturing processes.

In order to provide full-color capability in a stacked architecture of layered colorants, each colorant layer needs to be addressed with

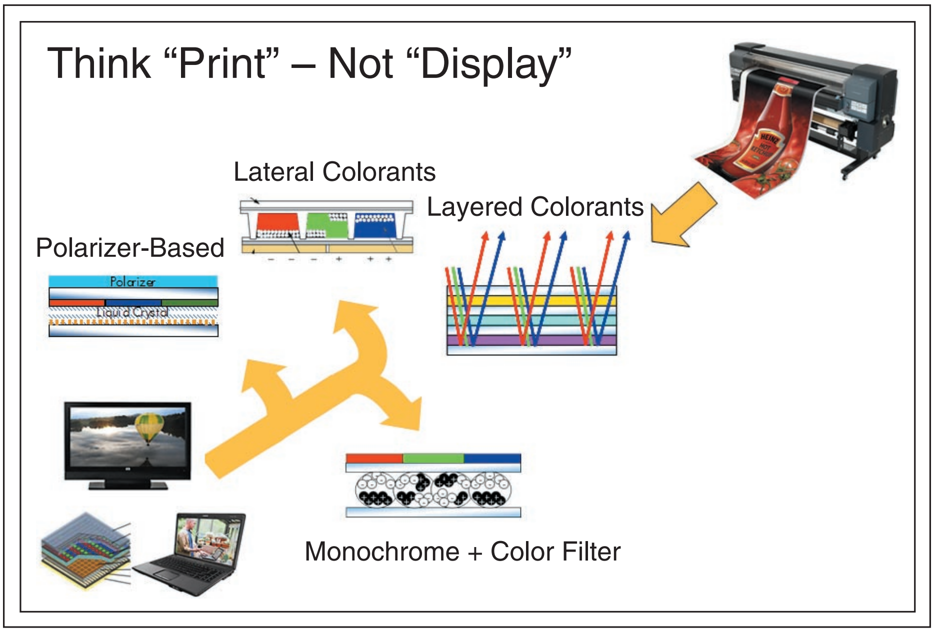

Fig. 1: *A “print-like” system architecture can be used as an approach to color reflective media.*

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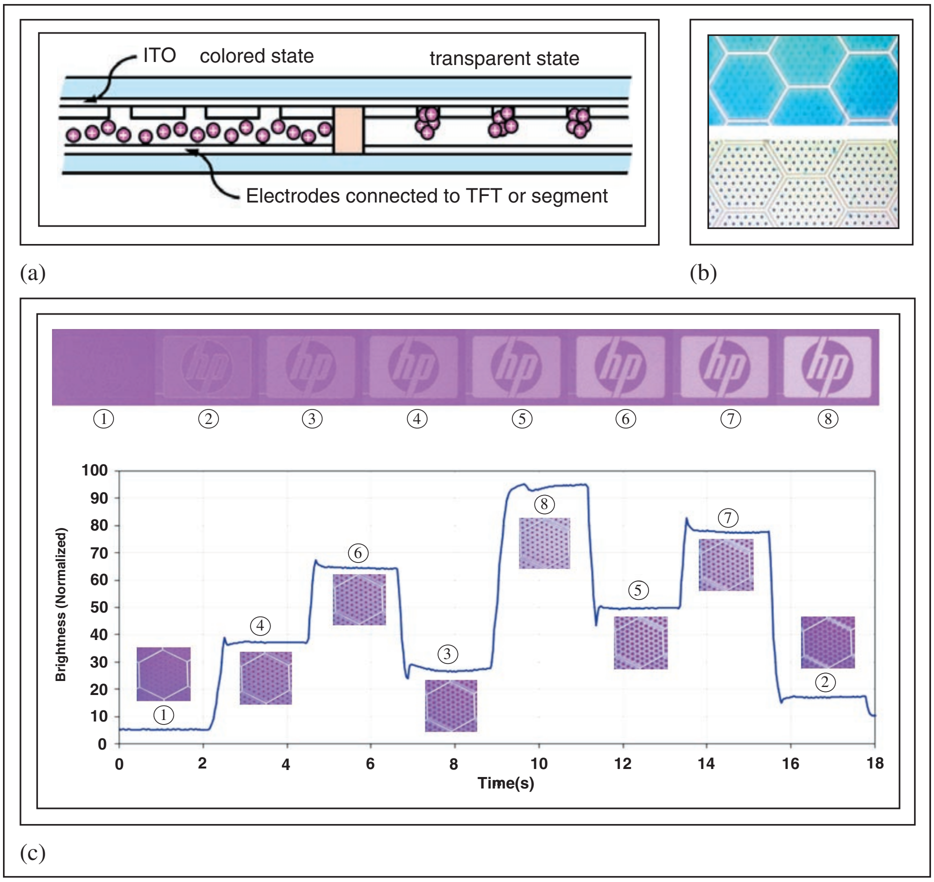

Fig. 2: (a) Cross section of the three-dimensional cell structure. (b) A novel device architecture using colored and transparent states. (c) A schematic of dynamic driving for eight levels of gray (= 3 bits).

electrical interconnect by integration of a suitably transparent matrix of driving electronics. This architecture also allows the potential for an optional backlit transmissive mode under low-ambient-light conditions. Consequently, HP is developing an active-matrix backplane technology based on transparent metal-oxide thin-film transistors (TFTs) that is compatible with existing glass (active-matrix LCD or AMLCD) fabs. Separately, the company has developed its self-aligned imprint lithography (SAIL) for low-cost R2R fabrication of active-matrix backplanes on plastic substrates. By using the SAIL process, it is possible to make single-layered electrophoretic displays using amorphous TFTs. Preliminary steps have been taken to adapt SAIL processing to transparent oxide semiconductors to permit eventual migration of the transparent active-matrix backplane to a flexible substrate using an R2R manufacturing process.[1]

A Print Paradigm

Reflective displays should be expected to provide a user interaction similar to that that of printed paper, plus the added versatility of dynamically refreshed images. Unlike emissive or transmissive displays, the reflective display does not generate any photons, but merely reflects ambient light as efficiently as possible via optical architectures and electrical designs in order to produce colorful images. Accordingly, we have adopted a "print" rather than a "display" approach to devising a system architecture, designing electro-optic switching layers and evaluating the resulting image in accordance with reflective media. Optically efficient system architectures require a shift of focus from polarizer-based lateral colorant or monochrome plus color-filter approaches to a system of electronically addressable layered colorants to achieve saturated color (Fig. 1), similar to the subtractive-primary approach adopted by the printing industry.

The visual performance of a reflective display is determined by perceived contrast (ΔL^*), color gamut (colorfulness), tonal resolution (gray levels), spatial resolution (pixels per inch or ppi), sensitivity to lighting and viewing angle, and switching-speed performance. The choice of electro-optic switching technology determines attributes such as tonal resolution, spatial resolution, viewing angle, and switching-speed performance, while the color gamut and contrast ΔL^* can depend strongly on the architectural arrangement of the system design.

Since advertisers in conventional printed media are accustomed to standards such as Specifications for Newsprint Advertising Production (SNAP) for newspaper ad inserts and the Specifications for Web Offset Publications (SWOP) for magazines and other high-quality printing, the performance of color-reflective electronic media should be evaluated by these standards if such media is to be a viable replacement for printed paper.

Meeting SNAP requires a white-state reflectivity of 60% (lightness L^* of 82), a value that many existing color-reflective technologies utilizing polarization effects or side-by-side color filters have difficulty achieving due to fundamental technology limitations. In order to meet these challenges while providing low power for mobility, good viewing angle for a paper-like experience, and rich color with ambient lighting, HP has developed a novel electro-optic device architecture with optically transparent and colored states based on proprietary electronic inks of primary subtractive colorants.

Figure 2 shows microscopic images of cells of this device architecture, which introduces a uniform distribution of dots where colorant particles can be compacted. Since the control of multiple electrokinetic forces leads to the compaction of charged colorants, the technology is termed "electrokinetic" media. Without an applied voltage, the colorant particles are spread uniformly within a cell and the display element is in the colored state. Under a bias condition that provides compaction of colorant particles into dot-patterned cavities, the display element produces a transparent state. The example shown in Fig. 2 with cyan ink demonstrates optical transparency (~80%) at low bias (< 15 V) with relatively fast switching (< 300 msec).

Plastic Substrates

HP has also developed a set of R2R processing capabilities for making fine-scale circuitry and physical features on plastic substrates that is compatible with the needs of reflective displays.[2] The R2R process, which utilizes imprint lithography and related techniques as key patterning steps, also offers significant cost advantages compared to conventional photolithographic processes. The tool set currently enables unit processes of coating, imprinting, plasma treatment, electrolytic and electroless plating, and laser micromachining. This low-cost R2R manufacturing platform has been applied to fabricate the flexible electrokinetic frontplane described here.

A photolithographically prepared master substrate is used to fabricate a flexible stamp. The stamp and imprint processes use proprietary resin materials to allow replication of multilevel three-dimensional patterns continuously down the web. This flexible frontplane media has been integrated with electrically addressable ink onto a backplane array made with transparent multicomponent oxide (MCO) thin-film transistors (TFTs). To modulate the optical state of each pixel, the pixel-plate electrodes are selectively activated through the TFT array, while the top electrode is maintained at a fixed reference bias. In the electrokinetic architecture, the out-of-plane switching geometry allows for the control of colorants between spread and compacted states, so various gray scales can be achieved by modulating the pulse width or pulse amplitude. Figure 2(c) shows eight levels of gray using direct-driven segments along with their respective images. Continuous dynamic driving to transition from one gray-scale level to another is possible without having to reset the colorant particles.

This frontplane technology has been applied to very thin and flexible color electronic-skin prototypes shown in Figs. 3(a)–(c) as well as the pixelated color reflective display shown in Fig. 3(d). The examples here provide an effective resolution >100 ppi for a frontplane with the transparent state at a low holding power for color reflective media (< 50 μW/cm^2 at < 15 V typical). Figure 3(c) demonstrates segmented prototypes with each primary colorant and Fig. 3(d) shows the image of what we believe to be the world's first electronic-ink-based pixelated stacked color reflective display using a three-layered cyan/magenta/yellow stack, each layer integrated with prototype TFT backplanes.

We have used a 1225 pixel (35 rows × 35 columns, 750-mm-square pixel size) prototype backplane to demonstrate integration feasibility of an active-matrix pixelated color reflective display.[3]

SAIL Process for R2R Active-Matrix Backplanes

Working with PowerFilm, Inc., HP developed a process for the R2R manufacturing of active-matrix backplanes using its self-aligned imprint lithography (SAIL). The primary goal in developing the SAIL process was not to make flexible displays, but rather inexpensive ones. We started with the single defining assumption that we would use R2R processes exclusively. Rather than adapting the existing active-matrix–on–glass architecture to R2R fabrication, SAIL aims to capitalize upon the strengths of R2R fabrication while avoiding its weaknesses. R2R processes can provide lower cost, better uniformity, and higher throughput than batch processing, particularly in large-area fabrication. However, the introduction of flexible plastic substrates presents a great challenge in layer-to-layer alignment because of the dimensional instability of plastic.

The SAIL process overcomes this alignment problem by imprinting a 3-D masking structure on top of the full stack of unpatterned thin films required for the thin-film-transistor (TFT) backplane. The multiple patterns required to create the backplane are encoded in the different heights of the masking structure. By alternately etching the masking structure and the thin-film stack, the multiple-layered patterns required for the backplane are transferred to the device film layers. Because the mask distorts along with the substrate, perfect layer-to-layer alignment is maintained regardless of process-induced distortion. Imprint lithography is ideally suited for R2R implementation because of its high resolution, high throughput, and ability to reproduce complex 3-D structures. The

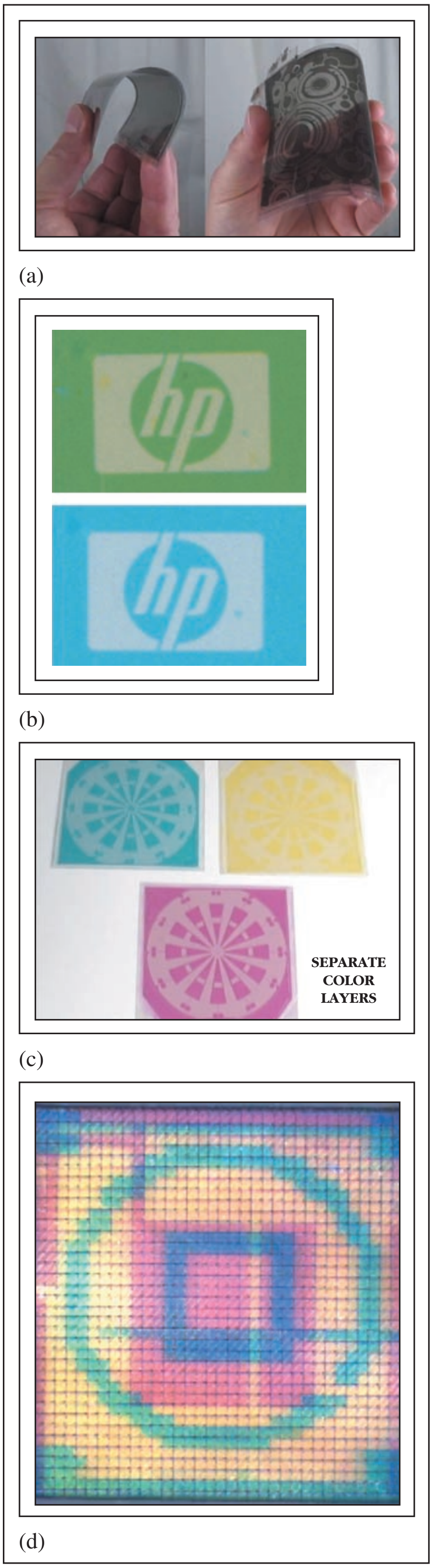

Fig. 3: Flexible reflective electronic-media prototypes include (a) flexible segmented electronic skins, (b) stacked segments that show additive (cyan plus yellow) and subtractive colors, (c) segmented examples with each primary colorant, and (d) an electronic-ink-based pixelated stacked-color reflective display.

imprint process begins with a master patterned to four different etch depths using a combination of conventional lithography and MEMS processes. This master is replicated onto the surface of a quartz roller. A web coated with photopolymer is wrapped partially around the quartz roller and UV-cured while in contact with the roller. We have imprinted 40-nm lines on 50-μm-thick polyimide and have developed materials that can maintain fidelity for thousands of impressions at throughputs of greater than 5 m/min.

The SAIL process flow is completely different from the conventional glass-substrate AMLCD backplane process, which consists of a sequence of deposition, alignment, and patterning steps. Each of the five or more thin-film layers is applied, typically with a vacuum deposition process, then individually aligned and patterned with photolithography. Each photolithography sequence involves application of a resist, alignment, and photo-imaging of a pattern to the resist, development of the resist, transferring of the pattern to the thin film via etching, and, finally, removal of the resist.

In the SAIL process, instead of sequential deposition and patterning of each material layer, the complete TFT stack including the top (source/drain) and bottom (gate) metal is first deposited in an inline R2R process. This enables high throughput and avoids contamination of critical interfaces produced by intervening patterning steps. Next, the 3-D masking structure (Fig. 4) is imprinted on top of the thin-film stack as described above. This single imprinting step replaces the five or more repeated applications of photoresist that dominate materials costs for the conventional AMLCD process.

The third phase of the SAIL process is a series of etches that transfers the patterns from the mask to the device layers. First, the complete TFT stack is etched away in any area not covered by the mask, and the gate metal is undercut until tunnels are formed in specially designed narrow regions. This enables the formation of crossovers and isolates the TFT gates. The imprinted mask structure is sequentially etched back level by level, with successive masking structure levels serving as etch masks to define the transistor channel and top metal patterns. Finally, the remaining polymer mask material is removed and the backplane is complete.

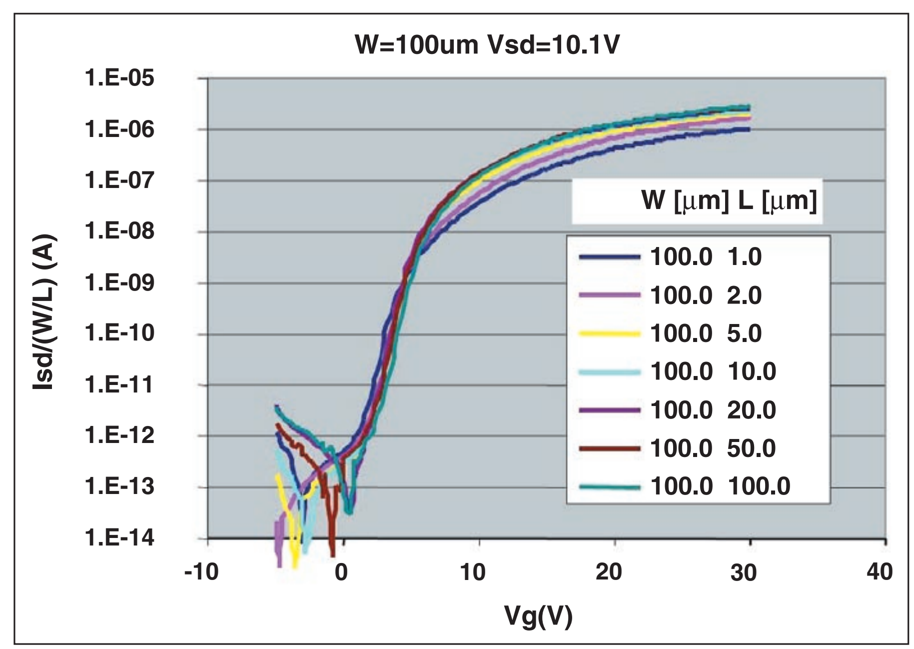

Fig. 5: The transfer characteristics are for a-Si SAIL transistors produced using roll-to-roll processing for various channel lengths.

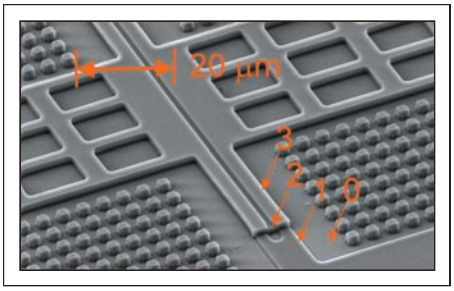

Fig. 4: This four-level imprinted mask is for an active-matrix backplane.

The electrical characteristics for completely roll-to-roll produced SAIL transistors are shown in Fig. 5 for different channel lengths. The scaling of the drain current as 1/*L* demonstrates that short-channel effects/contacts do not become a problem for channel lengths as small as 1–2 μm, even though the substrate is changing size by hundreds of microns. Thus, large on-currents are possible even with the relatively low mobility of a-Si.[4]

In 2009, we demonstrated, in partnership with E Ink, the world's first R2R fabricated displays using these processes (Fig. 6). This backplane is based on a thin-film stack composed of conventional hydrogenated amorphous-silicon (a-Si:H) semiconductor and silicon-nitride dielectric layers. The a-Si:H based SAIL process is currently being ramped to pilot production for single-layered electrophoretic displays.

R2R Process Cost Advantages

The primary motivation for R2R processing is cost: 1000 m of 1-m-wide 50-μm-thick polymer wrapped around a 150-mm diameter core has an outer diameter of 29 cm and weighs approximately 50 kg. One-thousand square meters of 0.7-mm-thick display glass weighs over 1700 kg. The cost of 1.5 × 1.8-m sheets of display glass (Gen 6) in large quantities

Fig. 6: This R2R fabricated active-matrix E Ink display was demonstrated in 2009.

is 3.2 times the cost of 50-μm-thick high-temperature polymer substrates for the same area. The dramatically lower cost of plastic compared to glass is a significant benefit, but perhaps more important is the simplicity of handling a flexible plastic web compared to the care which must be taken to work with fragile sheets of glass twice the size of a sheet of plywood and half the thickness of a CD.

R2R capital equipment costs are a fraction of those for flat-panel tools. This is, in part, due to ease of handling, but a second important contribution comes from the fact that most R2R processes operate in the steady state compared to the batch-oriented processing used in flat-panel tools. In batch processing, much of the cycle time is consumed in stabilizing transients resulting from changes in pressure, temperature, or other process variables as well as load and unload times. All of these issues can be eliminated in a steady-state R2R process. The footprint of the processing equipment is also reduced. Once a roll is mounted in a machine, a simple roll feed can move 1000 m of web through the process, eliminating the need for large, high-performance load locks and robotics.

As an example, we present the cost comparison between flat-panel and web-based patterning tools. The solid line in Fig. 7 shows the capital cost of a flat-panel stepper normalized by its throughput as a function of substrate size. Substrate size is represented by generation number. For reference, Gen 4 substrate size is 0.68 × 0.885 m, while Gen 10 is 2.85 × 3.05 m. The two pluses show the capital cost of the first two generations of R2R imprinters used in the SAIL process normalized by throughput and plotted on the x axis at the point where the throughput is equal to the flat-panel tool. In this case, the R2R tools follow a similar trend but are nearly two orders of magnitude cheaper. This cost difference is exaggerated by the fact that the imprint process is intrinsically a higher-throughput lower-cost process than step-and-repeat photolithography, but the minimum cost advantage in R2R deposition and etch tools is 5× over batch.

Another major opportunity for cost savings in R2R manufacturing is minimization or elimination of clean rooms. The incremental capital cost (excluding building shell and primary infrastructure) of a class 100 clean room is ~$10,000/m^2. In addition, the annual operating cost of the clean room may be as high as $1000/m^2. In the case of the SAIL pilot facility, if clean rooms were needed, they would double the capital cost of the factory. Flat-panel fabrication requires a clean room because the exposed surface of the substrate must be protected from particulate contamination at all times. In the case of R2R manufacturing, however, when the web is wrapped around the core, its surface is protected from contamination. If each tool enclosure provides a locally clean environment through HEPA filtration or because it is a vacuum system, then the web can be transported from tool to tool in a cassette with leaders much like that of a 35mm film cassette, thereby eliminating the need for the entire factory to be a clean room. Results from our current processing line, which uses a clean room only for in-process inspection, support this concept. Nevertheless, yield will be one of our greatest challenges in bringing this technology to market. The sources and effects of contamination are sufficiently different from those in batch processing that it will likely take many years to achieve yields equivalent to flat-panel displays.

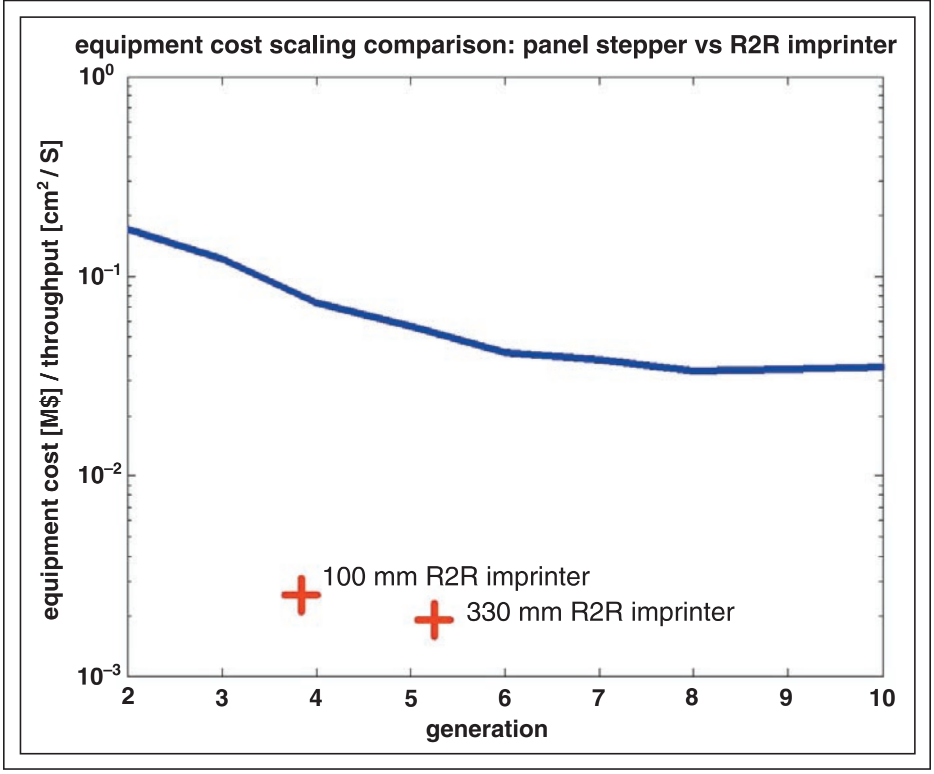

Fig. 7: In this comparison of R2R vs. flat-panel capital equipment costs for patterning, the solid line shows the capital cost of a flat-panel stepper normalized by its throughput as a function of substrate size. The two pluses show the capital cost of the first two generations of R2R imprinters used in the SAIL process, normalized by throughput and plotted on the x axis at the point where the throughput is equal to the flat-panel tool.

Transparent Metal-Oxide TFT integration

For many applications requiring inexpensive large-area electronics mounted on low-temperature substrates, TFTs based on multi-component oxide (MCO) channel semiconductor offer substantially higher performance than can be attained using today's ubiquitous a-Si:H TFT technology. Specifically, in addition to optical transparency, MCO-based TFTs offer performance advantages associated with enhanced mobility (on-current, operating speed, on-off ratio) and stability and are amenable to fabrication at lower temperatures than are needed for conventional a-Si:H processing. These devices promise to enable key advancements in thin-film electronics technology, including the extension of performance limits involving size, resolution, and refresh frequency for glass-based active-matrix LCD (AMLCD) panels; economical backplane manufacturing and suitable performance for new high-contrast thin organic LED (AMOLED) displays; on-glass integration of peripheral display circuitry such as row and column drivers; and the integration of high-performance and low-cost circuitry such as radio-frequency signals for RFID tags on low-cost plastic substrates. For these reasons, we are pursuing the development of a process for SAIL fabrication of MCO TFT active-matrix backplanes.

In addition to expected performance advantages, an MCO-based SAIL process may provide opportunity for process simplification and associated improvement in cost and throughput. For example, the typical amorphous-silicon stack includes an n^+ contact layer that must be removed from the channel region by a timed back-channel etch, whereas for the MCO-based device this additional contact layer and associated etch are believed to be unnecessary. Furthermore, the multi-component oxide-semiconductor materials can offer a unique opportunity to tune wet-etch characteristics via modification of cation ratio (*e.g.*, for the zinc-tin oxide system, etch rate varies dramatically as a function of Zn:Sn ratio for which electrical performance remains acceptable). Given the complex balance of etch selectivities and rates required for a functional SAIL process, this extra degree of freedom can be highly advantageous. These performance and process benefits provide ample motivation for the development of an MCO-based SAIL material stack and etch sequence, and thereby an economical and scalable approach to future high-performance flexible thin-film electronics circuits and systems.

Conclusion

A novel hybrid architecture adopting out-of-plane switching with in-plane optical effects that provides a transparent state with relatively fast-switching capability compared to other electrophoretic-based approaches has been demonstrated. Based on optical modeling, the technology presented here is predicted to approach the color gamut of the SNAP printing standard using a system of layered colorants, enabling a level of image quality that is critical to extending the technology to new markets such as digital signage. Future integration of HP's R2R-compatible frontplane and backplane technologies will demonstrate a scalable platform for low-power transparent print-like media that opens up a path toward eco-friendly bright full-color flexible electronic media.

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Solution-Coating Technology for AMOLED Displays

A new solution-coated AMOLED technology is poised for large-format commercial adoption. Improvements in intra- and inter-pixel layer uniformity have driven solution-coated AMOLED displays to match or exceed commercial evaporated AMOLED displays and AMLCDs for short-range uniformity.

by Reid Chesterfield, Andrew Johnson, Charlie Lang, Matthew Stainer, and Jonathan Ziebarth

SOLUTION-BASED coating methods for electronic-device applications are the focus of intense research efforts for many compelling reasons: reduced costs, improved performance, and new functionality, just to name a few. The breadth of applications for passive- and active-element solution-based coatings spans displays, lighting, solar cells, sensors, wireless devices for radio-frequency identification (RFID), and medical devices.[1] Here, the term active refers to using the semiconducting nature of the material as its primary function in a device; for example, in diodes and transistors. Most solution-based coating products that have achieved large-volume manufacturing are confined to passive elements where the electrical conductivity and/or optical or mechanical property of the solution-coated layer are the key to their functionality. Some examples are patterned bus lines, anti-reflective films, planarization layers, and phosphor layers. Few examples of solution-coated active devices have achieved large-scale commercial production.

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Active-matrix organic light-emitting diode (AMOLED) displays are a promising technology in which organic materials are employed to form key active electronic layers. Existing commercial technology for AMOLED displays currently uses thermal evaporation and fine-metal masks to deposit small-molecule materials, but has well-known difficulties in scaling to larger-sized glass.[2] Solution-coating offers the potential for significant cost savings in AMOLED production by reducing material waste and by coating on large-sized glass and may even push AMOLED technology to a cost lower than that for AMLCD technology. A detailed cost model predicts that solution-coated AMOLEDs could cost about 20% less than AMLCDs for small-sized displays,[3] with the savings growing for larger production lines and display sizes such as those for AMOLED TVs.

Solution Technology

DuPont Displays has developed a low-cost AMOLED technology that combines high-performance OLED materials tuned for solution-processing, coating techniques, and methods optimized for OLED layers and the utilization of existing flat-panel-display equipment. This OLED fabrication process is outlined in Fig. 1, in which two solution-coating methods are utilized: slot-coating for blanket layers and continuous nozzle printing for patterned layers. Figure 2 shows a vertical cross-section of an OLED device stack. The hole-injection layer (HIL) and hole-transport layer (HTL) are slot coated; the emissive red, green, and blue layers (EML) are nozzle-printed simultaneously, and a multi-layered cathode is blanket-evaporated. The brightness and color-uniformity specifications for flat-panel displays impose challenging thickness uniformity requirements for solution-coated OLED layers. The uniformity requirements are broken into several areas: long range (across the entire panel), short range (between neighboring pixels or inter-pixel), and within a subpixel (intra-pixel).

Figure 2 shows a schematic cross-section of high and low intra-pixel thickness uniformity and a corresponding example of a blue subpixel electroluminescent (EL) image. Inter- and intra-pixel thickness non-uniformity in the solution-coated layers can result in visual defects (mura) as well as non-optimal OLED device performance, and so our technical team developed several new analytical, metrology, and modeling methods to study and improve solution-coated layer uniformity.

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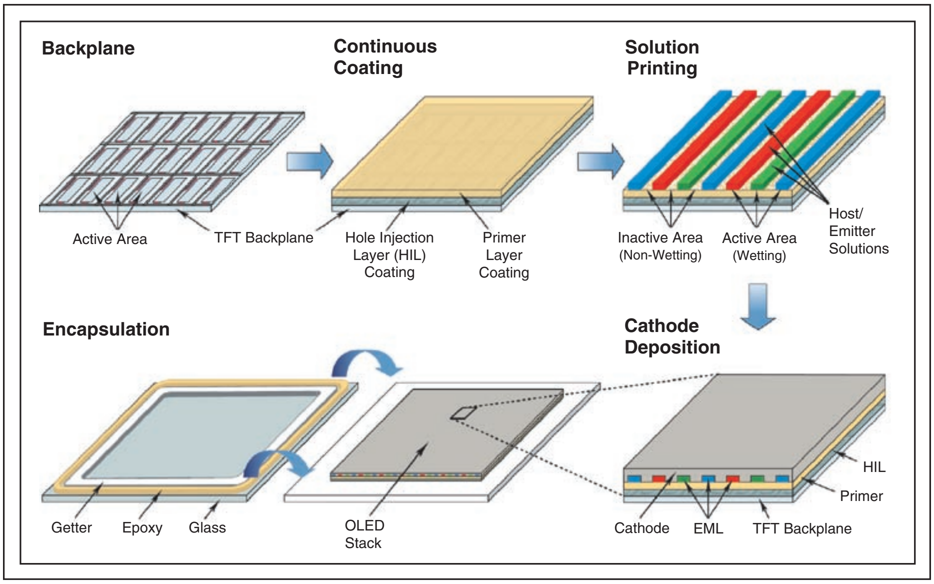


Fig. 1: Solution-coated OLED fabrication can be achieved using the above process flow.

85% *vs.* 65% for the spin-coated film. Generally, aperture percentage increases with increasing layer thickness and pixel dimension and apertures above 95% are achievable for larger pixels suitable for AMOLED TV. A previous report from DuPont (cited below) describes the slot-coating process and formulation strategy to optimize coating and drying performance in OLEDs.[5]

Continuous nozzle printing utilizes a laminar liquid jet that issues from a fixed orifice and then impinges on the substrate. The printing process operates by continuously moving the liquid jet across the substrate in alignment with previously defined wetting and non-wetting areas. The printhead traverses back and forth along the x-axis of the printed plate while the stage (substrate) proceeds in increments along the y-axis in synchronization with the head. Commercially acceptable cycle times can be obtained by printing multiple arrays of jets using x-axis traverse speeds

Slot-Die Coating is the preferred commercial solution-coating technique for preparing thin uniform blanket layers, and this technique has been scaled up to (at least) Gen 8 substrates for flat-panel-display processing. Slot-die coating is also being developed for use in general-lighting-based OLED applications.[4] Figure 3 (top) shows optical profilometer data plotted as a contour map of our company's HIL slot-die coated onto a 150 × 150-mm glass substrate. In this sample layer, we achieved, via slot coating, better than ±3% long-range layer thickness uniformity for a layer as thin as 600 Å.[a]

Through optimization of formulation, die geometry, coating, and drying, we found that slot-die coating can deposit 2–10-μm-thick wet layers over relatively tall (~1 μm) display topography such as bus lines, pixel-defining layers, and circuit vias. However, differences in wetting due to surface material type (for example, ITO *vs.* photoresist) and surface-tension gradients can cause thickness non-uniformity in the dried film that must be minimized. We define thickness aperture, a figure of merit for characterizing intra-pixel thickness uniformity, as the percentage of pixel cross-section within ±10% of the center of pixel thickness (nominal target thickness). Figure 3 shows a comparison of spun *vs.* slot-die coated subpixel HIL layer thickness, for a 225-Å target thickness. The slot-die coated layer has a much higher thickness aperture at

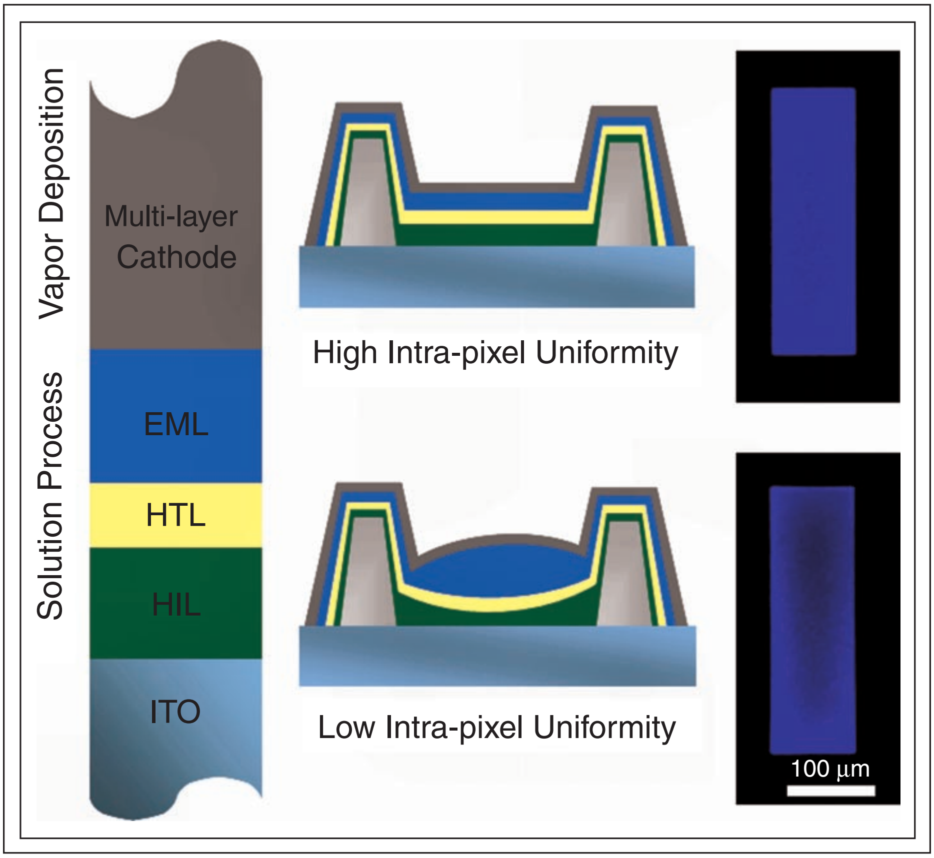


Fig. 2: At left is an architectural cross-section of a solution-processed OLED device. The middle shows a schematic cross-section of high and low intra-pixel uniformity in OLED layers (not to scale) and at right is a corresponding example of blue-subpixel EL images.

up to 5 m/sec.[6] Nozzle printers suitable for printing solution layers for large-scale AMOLED displays have been developed together with Dainippon Screen Mfg. Co., Ltd. (Kyoto, Japan) and a multi-nozzle printer capable of Gen 4 (refers to stage size) substrates has been installed at DuPont Displays' pilot facility in Santa Barbara, California.

The key elements of nozzle printing are

- Establishing a stable laminar jet.
- Scanning the jet across the substrate.
  - During this time, the ink spreads on the substrate due to inertia and retracts back to the wetting region of the previously formed containment pattern.
- Advancing the substrate while the nozzle is off the printed region.
- Drying to a uniform thickness profile.

Several approaches for forming a containment pattern suitable for printing OLED displays are described in the literature. DuPont Displays' proprietary ink-containment pattern (Fig. 2) is created during the OLED-fabrication process and requires no physical containment structures. The containment process forms wetting and non-wetting regions on the substrate to help contain the red, green, and blue EML inks; the main purpose of containment being to prevent cross-contamination between the inks.

While the length over which the liquid jet is stable determines the lower limit for flow rate, the upper limit is set by the orifice (nozzle) opening and the gap between the orifice and substrate. Laminar jet stability has been studied extensively, and these studies have explored the effects of jetting parameters (orifice size, fluid velocity, and motion of the surrounding gas) and liquid properties (surface tension, viscosity, changing composition, and viscoelasticity).[7]

We captured high-resolution high-magnification images of our printing jets and measured the stable length. For long stable jet lengths, the predictions of a literature model[8] are in reasonable agreement with our observations. However, the model severely overpredicts the lower limits of stable jet length. We used a value of the initial jet perturbation $\eta_{0/a} \sim 0.07\%$ in the Mahoney-Sterling model, which is typical in the literature. Experimentally, we found that the disagreement with the model is due to distortion of the jet as it begins to wet the nozzle face. Upon impact, the jet spreads due to inertial forces. Obviously, spreading must be controlled to prevent color contamination, *e.g.*, printing green ink into a blue subpixel. The need to control spreading generally determines the upper limit on ink flow rate.

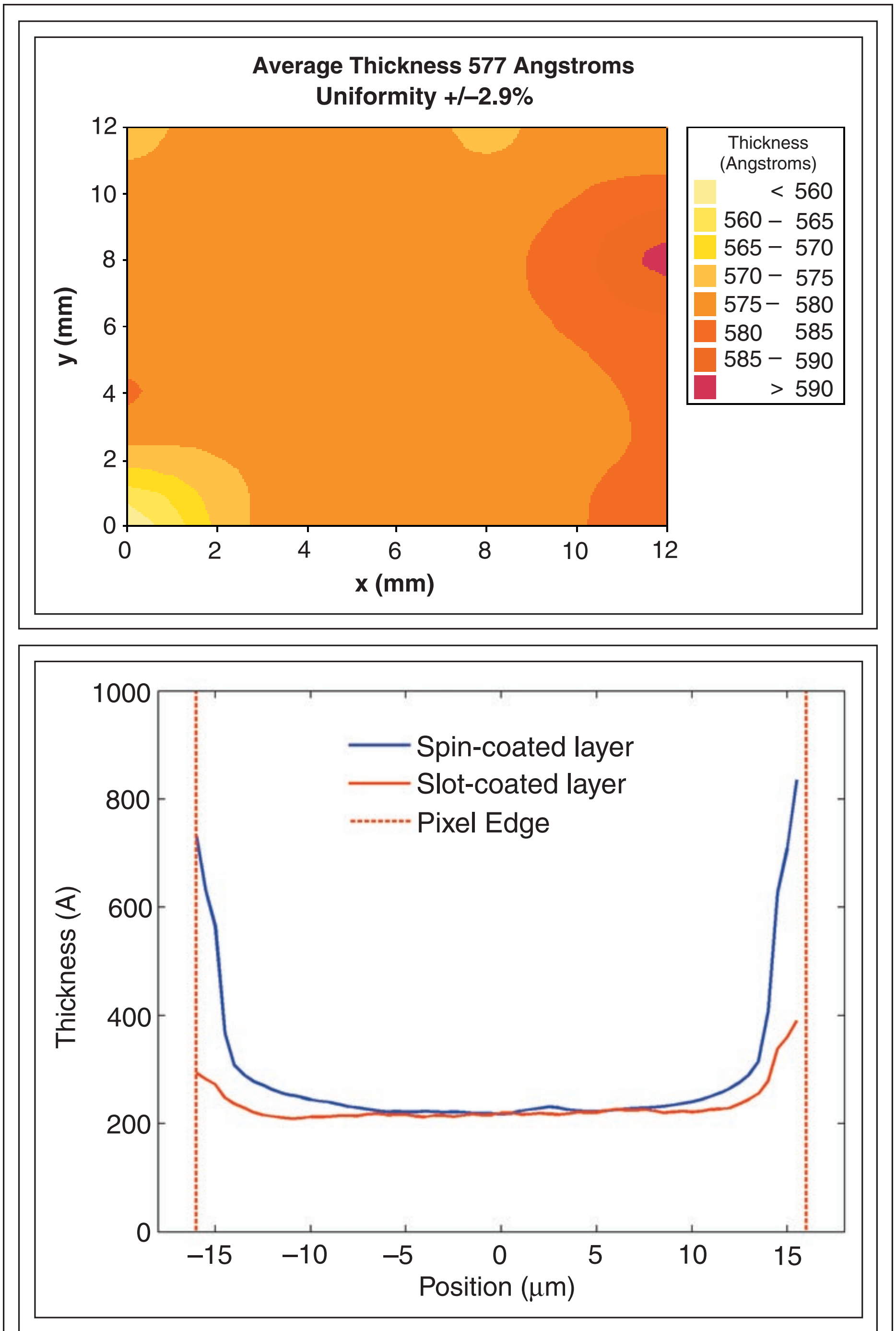


Fig. 3: At top is a thickness contour map of an HIL slot coated on a 150 × 150-mm bare glass substrate; the coating has a uniformity of ±2.9% of the 577-Å layer. At bottom is shown a stylus profilometer measurement of a subpixel (cross-section), comparing spin vs. slot-coated layer thickness within a subpixel.

We performed computational fluid-dynamic (CFD) modeling to better understand inertial spreading in nozzle printing. All CFD modeling used FLOW-3D, a volume of fluid simulation package from Flow Science, Inc., located in Santa Fe, New Mexico (www.flow3d.com). Figure 4 shows a sample CFD simulation output of axisymmetric impingement of a laminar jet on a surface. To verify the model's ability to predict inertial spreading, we simulated hydraulic jumps, which have previously been well-described and pictured at larger length scales.[9] We found no literature data for hydraulic jumps at lengths typical of our printing process, so we obtained jump radii (R_h) using the setup shown in Fig. 4. We obtained good agreement between CFD simulations and our experimental results.

Figure 4 (lower) shows a CFD simulation of a simple printing flow. The jet moves across a substrate with a surface-tension pattern that prevents overflow to neighboring print lanes. The top-view image (middle) shows the wet line deposited as the jet passes. The dashed red lines represent the boundary of the wetting region, with a non-wetting surface outside the boundary. Initially, the liquid spreads onto the repellent surface due to inertia and retracts back to the containment boundaries as surface tension establishes an equilibrium meniscus shape. The graphic on the right shows a time series of the line profile, starting at the point of widest spreading and progressing toward the final equilibrium shape.

Customized metrology and analytical methods have been developed in our laboratories for measuring thickness and luminance uniformity in our solution-coated AMOLED displays. Excellent intra- and inter-pixel and long-range thickness uniformity is required across several orders of magnitude in length scale, from tens of microns to tens of centimeters or larger. As a result, we have developed multiple techniques to study and optimize the uniformity of the liquid deposition and drying processes.

The presence of pixel wells complicates drying by distorting the meniscus. Careful control of the drying rate, surface tension, and viscosity are important factors for achieving uniform films. We constructed a drying model to help us understand and optimize the drying process. Practical inks often contain multiple solvents, and mixture evaporation is best described using non-ideal vapor pressures. We estimate the activity coefficients

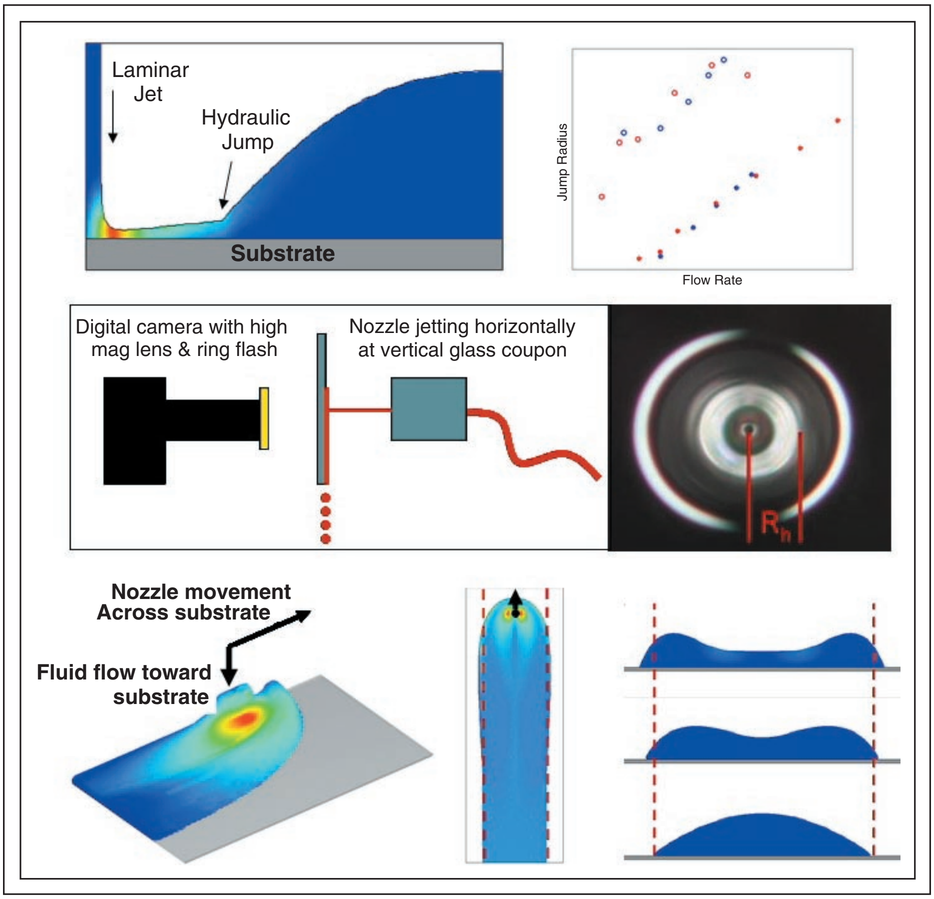


Fig. 4: *At upper left, a CFD simulation of axisymmetric impingement of a laminar jet on a surface is depicted. At the hydraulic jump, the fluid slows and the liquid-layer height increases significantly. Color (blue to red) indicates magnitude of radial velocity (low to high). At right is shown the hydraulic jump radius for two nozzles plotted vs. flow rate. Blue symbols represent experimental data and red symbols represent CFD simulation. The upper set of results has been offset vertically for clarity. At middle is a schematic of the hydraulic jump measurement apparatus and a sample image used to measure R_h. At lower left is a perspective view of CFD simulations of a simple printing flow. The jet moves across a substrate with a surface-tension pattern that prevents overflow to neighboring print lanes. The hydraulic jump is distorted by the movement of the nozzle across the surface. Colors indicate the magnitude of the lateral fluid velocity. Lower-middle is the top view: the wet line is deposited as the jet passes. The dashed red lines represent the boundary of the wetting/non-wetting region. Lower right: substrate plane view. A time sequence shows liquid spreading onto the non-wetting surface due to inertia and retracting to an equilibrium shape on the wetting pattern.*

for the ink solvents using the UNIFAC (Universal Functional Activity Coefficient) group contribution method.[10] Using an adaptive time step model, with correlations fit to surface tension and viscosity data, allows us to predict the evolution of fluid properties through the drying process in order to control the resultant film shape and optimize for flat films.

To characterize the intra-pixel and long-range uniformity of a printed layer, we used a standard stylus profilometer to measure multiple spots on the printed display. In this technique, we left an unprinted pixel row with identical underlayers next to the printed pixel row. We then subtracted the underlying layers from the unprinted row to get a measure of the film thickness as a function of position within the pixel. Automated software was developed to analyze large data sets across various display designs and resolutions. Figure 5 (left) shows thickness profiles for EML films with good uniformity measured at 16 locations across a 150 × 150-mm printed substrate. This data set has a standard deviation of 2 nm, with a 38-nm center-of-well thickness resulting in ±5% long-range uniformity, illustrating the high level of long-range uniformity in our printing process. A thickness aperture metric, similar to that described for slot-coated layers, helps to numerically describe the intra-pixel uniformity; typically a >95% thickness aperture is achievable for pixels suitable for AMOLED TVs. This custom measurement system provides direct and immediate feedback for process development without requiring the fabrication of full OLED devices. Consequently, we are able to quickly tune our ink formulation and process conditions in order to optimize intra-pixel and long-range uniformity.

In combination with measuring the intra-pixel thickness uniformity of the slot-die-coated and nozzle-printed layers, we can also measure the uniformity of light emission from the pixels in a completed device. Here, we use a microscope camera to obtain high-resolution images of discrete pixels. We then use custom image-analysis software to measure the luminance intensity across the pixel. This technique yields profiles that are analogous to the film-thickness profiles described previously; an example is shown in Fig. 5 (right). It is particularly useful to correlate the thickness profiles for the solution-processed layers with the luminance-uniformity measured from the completed OLED to improve performance.

It is well known that jetting simultaneously out of multiple orifices presents a challenge for printing technologies, due to short-range luminance variation that can occur between subpixels of the same color, sometimes called stitching or swath marks.[11] The authors previously described this problem for nozzle printers, as well as several implemented fixes in a 2009 SID Symposium presentation, "Multi-Nozzle Printing: A Cost-Effective Process for OLED Display Fabrication."[6] In nozzle printing technology, each nozzle acts as an independent flow element with separate mass-flow controllers, so it is very important that nozzle flows match in order to produce films of identical thickness in neighboring subpixels. As a consequence, we developed techniques to characterize the uniformity from subpixel to subpixel.

To compare the deposited volume of ink between two or more nozzles, we used an optical profilometer to obtain images of printed lines on smooth glass substrates. We then computed the volume of each line, using software we developed for this purpose. Next, this method was calibrated using measurements made on a plate where flows had been intentionally offset between two nozzles. We have confidence that this technique is capable of studying differences in deposited volumes of less than 1%.

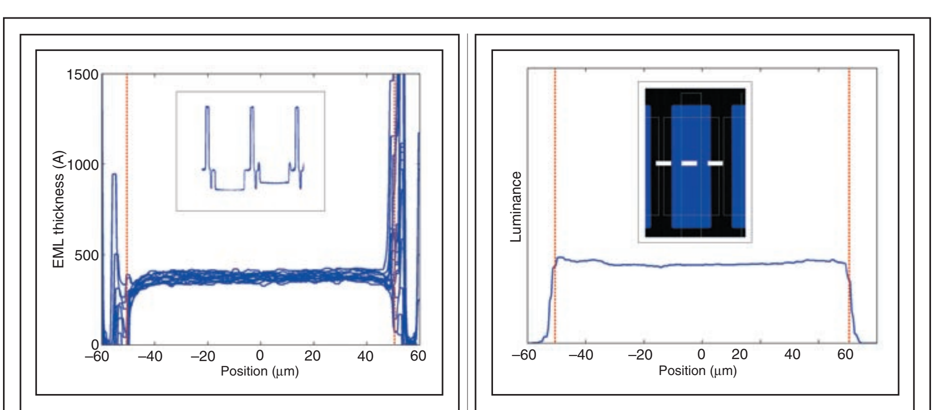


***Fig. 5:** At left are printed film profiles obtained with a stylus profilometer and a custom automated software analysis program. The inset shows a sample of the raw scan data where a printed row is located next to an unprinted row with identical underlayers. The red dashed lines represent the edge of the pixel. On the right is an example of a luminance intensity plot used to analyze intra-pixel uniformity.*

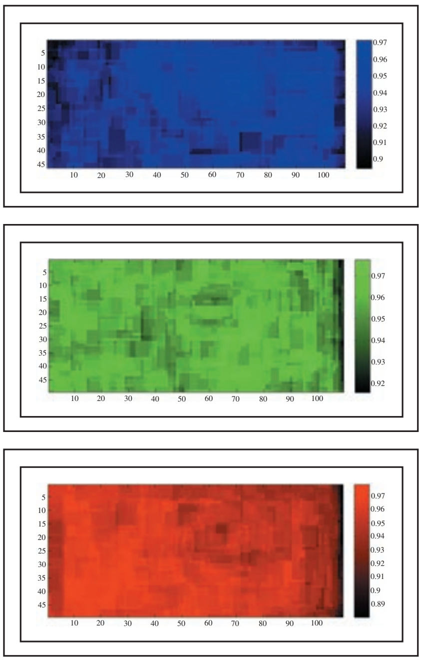
Short-range luminance uniformity (SRU) is a complicated display metric due to the variety of resolutions, viewing environments, and human physiological responses. A well-defined automated machine-vision inspection metric has yet to be defined. To examine the effect of coating uniformity, and, in particular, printing-layer inter-pixel uniformity in our AMOLED displays, we used an SRU specification that had previously been reported to compare commercial AMLCD and AMOLED technology.[12]

We obtained a map of the luminous intensity of each subpixel using a linear high-resolution CCD camera in conjunction with a video-photometer and custom image-analysis software. We then used formulae[13] that determine the ratio for the maximum and minimum luminance to calculate the SRU of each subpixel and neighbors in an 8 × 8 block. We repeated the analysis for each subpixel in the display to generate SRU maps as shown in Fig. 6. The overall SRU for the display is an average of all the block SRU values.[14] A commercial AMLCD measured by this method had an SRU of 0.93. DuPont solution-processed AMOLED displays have equal or greater SRU values for each color, thus demonstrating the high uniformity of this solution-coating technology.

Our OLED materials have demonstrated superior performance. Table 1 shows printed OLED device performance of current generation materials using a common thickness for all layers except the EML.[15] All printed device data are collected from devices fabricated in an ambient atmosphere clean-room environment, using the same types of processing techniques planned for commercial manufacturing of solution-processed OLED displays.

In order to prove performance, DuPont Displays fabricated multiple solution-coated AMOLED displays for the SID's Display Week 2010 exhibition. Figure 7 shows front- and side-view images of a 4 × 4 array representing a segment of a 40-in. HDTV. The 16 AMOLED displays used in this demonstration were fabricated similarly to the one for which luminance SRU was measured (Fig. 6).

This solution AMOLED technology can be leveraged into other solution-based organic-semiconductor applications such as OLED lighting and organic solar cells. Specifically, we are extending the materials, processing, and architecture know-how generated in



Summary	
Color	U_{sh}
Blue	0.94
Green	0.94
Red	0.95

Fig. 6: Shown is a uniformity map of SRU (UR_{ij}) over a large section of a printed AMOLED display and the average SRU (U_{sh}) for each color (table). These SRU values equal or exceed the values reported for commercial AMLCDs.[12]

Table 1: This printed RGB test coupon performance summary uses a T50 adjusted OLED-TV lifetime (conservatively estimated using all pixels on, 100% of the time) and measured efficiency for simulated OLED-TV conditions.[16]

Color	CIE 1931 x,y	Efficiency (cd/A)	Printed T50 lifetime (hours)
Red	0.65, 0.35	15.1	29,000
Green	0.26, 0.64	21.9	230,000
Blue	0.14, 0.14	6.0	40,000

Fig. 7: This prototype AMOLED-TV array was made with DuPont's OLED solution-processing technology and materials and was exhibited at the Society for Information Display's Display Week 2010. The array is composed of 16 4.4-in.-diagonal 55-ppi displays, representing a segment of a 40-in. HDTV.

AMOLED to color-tunable white lighting under a Department of Energy Solid State Lighting Project titled "Solution-Processed Small-Molecule OLED Luminaire for Interior Illumination." The white-lighting project aims for 40 lm/W using separate printed yellow, orange, and blue emitter layers, which allow color tuning of the luminaire white point.

Summary

DuPont Displays has developed a full set of high-performance materials and solution-processing technology to address the high cost of manufacturing AMOLEDs. We optimized our coating processes to be cost and performance competitive with existing commercial vapor-deposition technology. The brightness and color-uniformity specifications for flat-panel displays present challenging thickness and uniformity requirements for solution-coated AMOLED layers. Using a wide variety of custom modeling and analytical approaches, we have developed short- and long-range film-thickness control and uniformity that is commercially viable at large glass sizes. These coating technology improvements should extend to other solution-based applications as well.

Acknowledgments

The contributions of all members of the technical teams at DuPont OLEDs, both in Santa Barbara, California, and Wilmington, Delaware, are gratefully recognized.

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[a]Formula for uniformity = $\pm[(T_{max} - T_{min})/(T_{max} + T_{min})]$.

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[13] $$Ush = \frac{\sum_{i=0}^{n-1}\sum_{j=0}^{m-1} Ur_{ij}}{n \times m} \text{ where } Ur_{ij} = 1 - \frac{L_{64\max} - L_{64\min}}{L_{64\max}},$$

$$L_{64\max} = \max_{i=0\ldots7,\, j=0\ldots7} L_{ij},\; L_{64\min} = \min_{i=0\ldots7,\, j=0\ldots7} L_{ij}$$

[14]Shorted pixels and dead pixels were omitted for this analysis.

[15]R. Pflanzer, *IMID Symposium Digest* (2010).

[16]No outcoupling enhancement efficiency. Measurement assumes Lambertian emission profile. Common architecture converted to 200 nits front-of-screen (white point CIE x,y = 0.31, 0.32) with 40% aperture ratio, 46% transmission circular polarizer, driven at a 100% duty cycle. Lifetime data reported at 20°C. ■

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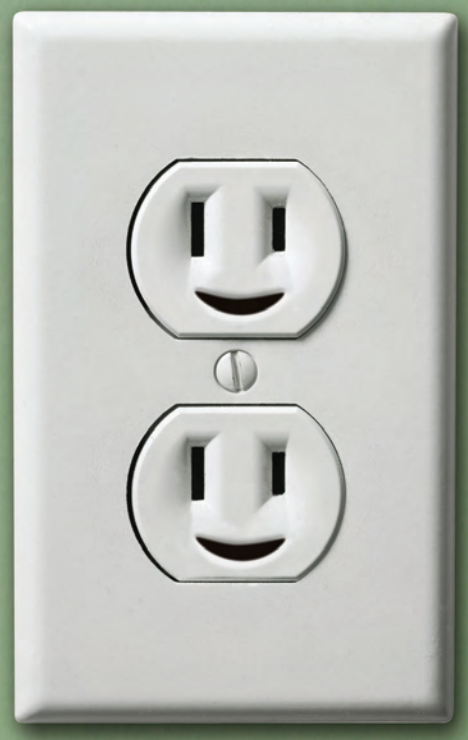

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editorial

continued from page 2

EMI Management." With a combination of historical context and a survey of the new innovative structures being developed by 3M, the authors paint a nice portrait of some of the interesting ways new film designs can enhance displays.

Roll-to-roll manufacturing processes for applying liquid coatings on flexible substrates have been a staple of the materials industry for decades. Recent innovations have included concepts for printing OLED and other display materials onto flexible substrates to make high-volume low-cost displays. Now HP has developed a roll-to-roll methodology for printing multiple layers of proprietary electronic inks of primary subtractive colorants to make what it terms "electrokinetic media." Authors Jong-Souk Yeo *et al.*, from HP Labs, describe this development in "Paper-Like Electronic Media: The Case for R2R-Processed Full-Color Reflective Displays." There are many interesting facets to this development, including the possibility of manufacturing reflective active-matrix displays on flexible backplanes with transparent oxide transistors. But for me, the most intriguing is the concept of making color not by using conventional R-G-B discrete reflective regions, but by layering electrically switchable layers of C-M-Y that can be individually addressed to become transparent or opaque in at least eight discrete gray levels each. This novel approach could be one of those ideas that changes the way we look at engineering reflective displays.

Finally this month, imagine being able to fabricate an active-matrix OLED display entirely with a conventional coating process such as nozzle jet printing. In their article titled "Solution Coating Technology for AMOLED Displays," authors Reid Chesterfield, Andrew Johnson, Charlie Lang, Matthew Stainer, and Jonathan Ziebarth from DuPont Displays describe their very clever and well-engineered process to fabricate complete AMOLED pixels, which they demonstrated in finished displays at Display Week 2010. I think their analysis is impressive, and this accomplishment obviously involved a great deal of dedicated work. At the end, the process itself appears almost deceptively simple to implement, and I am looking forward to seeing more progress and hopefully commercialization in the near future.

For many of us, 2010 was a tough year in business terms. There is economic growth out there, but the gains are hard-won, and the business of displays is far from fully predictable these days. I do not know at press time of this issue how the full year will net out in terms of commercial sales and revenue for TVs and other electronics, but based on the recently announced reductions in output at some major LCD manufacturers, I do not think the numbers will be awe-inspiring. The same may go for the industrial and specialty markets, though I believe those are showing more promise for sustained growth. I hope we will not need to endure another year of halting starts between short bursts of recovery, which can be draining on any business team. It is hard to make investments in new technology when the timeline to achieve the required economic return is unpredictable. It is also hard to make hiring decisions when the revenue forecast is foggy. Expansion and investment are the keys to capitalizing on the recovery, but you need capital and cash flow, which makes every new undertaking riskier and more uncertain than it should be. Nonetheless, as you read through the rest of this issue, I hope you get re-inspired to tackle some tough problems of your own and realize that regardless of the business climate, it is clear that innovation is alive and well, especially in the less-publicized corners of the display business such as films and coating technology. ■

guest editorial

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The third article, "Solution Coating Technology for AMOLED Displays," by Reid Chesterfield *et al.* from DuPont Displays, presents an overview of perhaps the most advanced implementation of solution-processed electronic material coatings and their use for large-area electronic device fabrication to date. Most solution-based electronic coatings found in large-scale manufacturing are typically used for less-demanding passive devices. The DuPont team presents an overview of a systematic approach for developing solution-based coating methods for ultra-thin semiconductor layers and device fabrication on large-area glass substrates, based on engineering the OLED material itself, the printing equipment and process, and the necessary substrate engineering necessary to create a patterned RGB three-color OLED display architecture. As highlights, impressive long-range uniformities of +3% for organic semiconductor layers as thin as 600 Å are shown, and instrumental development of customized metrology and analytical tools to characterize and develop these advanced processes is discussed.

Though the selection of articles was necessarily small, we hope that these snapshots of current developments in display materials, processing, and device architectures will provide glimpses into the exciting future ahead of us, where higher performance displays will emerge, as well as new applications that will result from hybridizing these advanced display technologies with emerging ones.

Last but not least – a happy, healthy, and prosperous new year to all! ■

***Ion Bita** is Staff Engineer/Manager, Display Technology Center, at Qualcomm MEMS Technologies. He can be reached at ibita@qualcomm.com.*

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The following papers appear in the February 2011 (Vol. 19/1) issue of *JSID*.
For a preview of the papers go to sid.org/jsid.html.

Papers by Subject Categories

Active-Matrix Devices and Circuits

16–20 **Amorphous-oxide TFT backplane for large-sized AMOLED TVs**
Yeon Gon Mo, et al., Samsung Mobile Display, Korea

Cognitive and Interactive Displays and Systems

70–78 **The technologies of in-cell optical touch panel with novel input functions**
Kohei Tanaka, et al., Sharp Corp., Japan; Chris Brown, Sharp Laboratories of Europe, Ltd., UK

Display Backlighting

37–47 **A monolithic segmented functional light guide for 2-D dimming LCD backlight**
K. Käläntär, Leiz Advanced Technology, Japan

48–56 **Novel LCDs with IR-sensitive backlights**
Kwonju Yi, et al., Samsung Advanced Institute of Technology, Japan

100–105 **High-luminance and luminous-efficacy mercury-free flat fluorescent lamp (MFFL) with local-dimming functionality**
Jae-Chul Jung, et al., Seoul National University, Korea

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K.-M. H. Lenssen, et al., Philips Research, The Netherlands

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Jia-Ming Liu, et al., ITRI, Taiwan

94–99 **Improvement in image quality of a 5.8-in. OTFT-driven flexible AMOLED display**
Yoshiki Nakajima, et al., Japan Broadcasting Corp. (NHK), Japan

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Sejoon Oh, et al., Tohoku University, Japan

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87–93 **A new wettability-control technique for fabricating color OLED panels by an ink-jet-printing method**
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Ryota Sato, et al., Tohoku University, Japan

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29–36 **Control of subjective depth on 3-D displays by a quantified monocular depth cue**
Shuichi Takahashi, et al., Sony Corp., Japan; Kazuya Matsubara, et al., Tohoku University, Japan

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