FLEXIBLE AND STRETCHABLE TECHNOLOGY

Information DISPLAY

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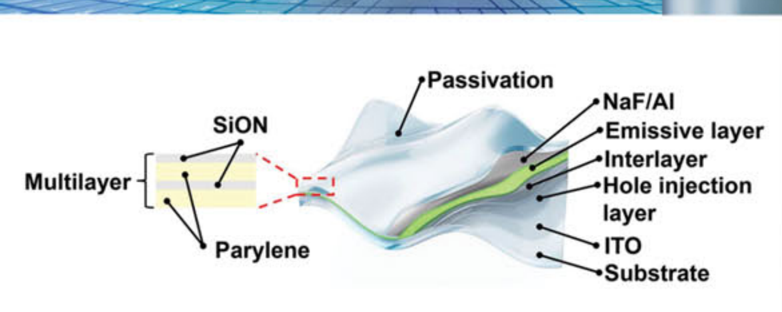
The Future of Flexible Displays

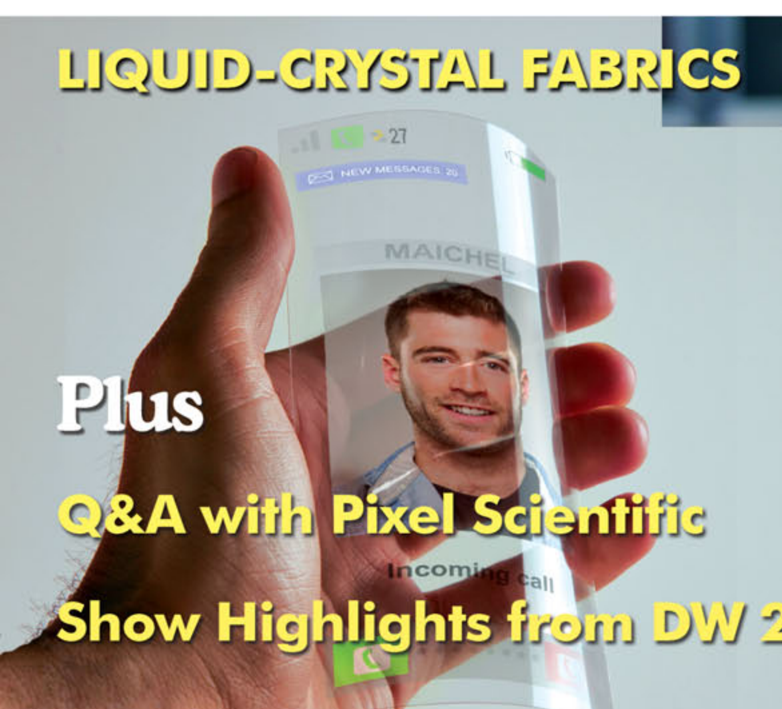
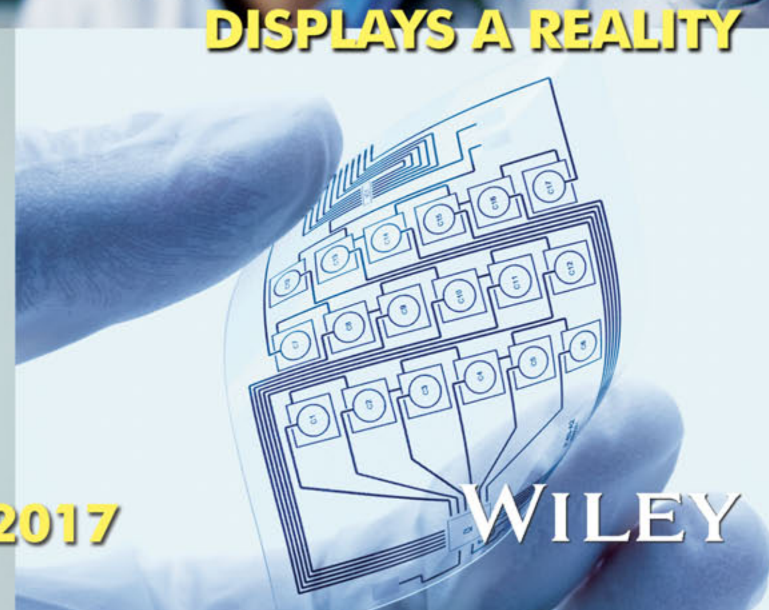
NEW MATERIALS FOR FLEXIBLE SUBSTRATES

STRETCHABLE OXIDE TFT FOR WEARABLES



LIQUID-CRYSTAL FABRICS

MAKING STRETCHABLE DISPLAYS A REALITY

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ON THE COVER: *Flexible, stretchable technology is the next frontier for the display industry. The schematic image at center left is courtesy of Yongtaek Hong, Seoul National University.*

Cover Design: Acapella Studios, Inc.

In the Next Issue of *Information Display*

Display Week 2017 Review

- Augmented Reality/Virtual Reality
- Display Materials
- Automotive Displays
- Digital Signage
- 3D and Near-to-Eye Displays
- Metrology

And

2017 Best in Show and I-Zone Winners

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contents

2 ***Editorial:*** **Stretchable Displays, Summer Days**
By Stephen P. Atwood

3 ***Industry News***
By Jenny Donelan

4 ***Guest Editorial:*** **Stretch of Imagination**
By Ruiqing (Ray) Ma

6 ***Frontline Technology:*** **Stretchable Displays: From Concept Toward Reality**
Stretchable displays are now being developed using strategies involving intrinsically stretchable devices, wrinkled ultra-thin devices, and hybrid-type devices.
Yongtaek Hong, Byeongmoon Lee, Eunho Oh, and Junghwan Byun

12 ***Frontline Technology:*** **Stretchable Oxide TFT for Wearable Electronics**
Oxide thin-film transistors (TFTs) in a neutral plane are shown to be robust under mechanical bending and thus can also be suitable for TFT backplanes for stretchable electronics.
By Xiuling Li and Jin Jang

16 ***Frontline Technology:*** **Developing Liquid-Crystal Functionalized Fabrics for Wearable Sensors**
Looking to the future, we can envision how liquid-crystal fabrics can be designed to respond to chemical and biological stimuli, signaling the presence of bacteria and viruses, and opening the potential for wearable medical sensors.
By Junren Wang, Antal Jákli, Yu Guan, Shaohai Fu, and John West

22 ***Making Displays Work for You:*** **New Polymer Materials Enable a Variety of Flexible Substrates**
The Pylux family of polysulfide thermosetting polymers (PSTs) has been developed to enhance manufacturing options for a wide range of flexible displays and electronics.
By Tolis Voutsas, Radu Reit, Adrian Avendano, David Arreaga, and John Dupree

28 ***Show Highlights:*** **Display Week 2017 Daily Reports**
Foveal rendering, high-resolution automobile lamps, flat-panel speakers – and friends – were only a few of the highlights that *Information Display*'s experts reported on from Display Week 2017 in Los Angeles.
By Information Display *Staff*

32 ***Market Insights:*** **Q&A with Pixel Scientific**
By Dick McCartney and Jenny Donelan

35 ***SID News:*** **Honors and Awards Nominations**

40 **Corporate Members and Index to Advertisers**

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

editorial

Stretchable Displays, Summer Days

by Stephen P. Atwood

There was a long line at the booth, and I debated whether to wait in it on the first day of the exhibition. Something was being shown in the back room of the booth that was obviously interesting to people, but there was almost no hint of what it was from the front. A clever ruse that would either pique my interest or make me wish I had not invested the time. Well, I did invest the time and it was worth it. In that dark alcove in the Samsung booth at Display Week 2017 was a demonstration of a stretchable AMOLED display that was as honest as it could get.

The roughly 9-in. display was shown in such a way that you could clearly see both the front-of-screen operation and a continuous, substantial, 2-dimensional mechanical deformation from the center region – enough that I feared it might fail after a short number of cycles. But as far as I know it kept working for all three days of the exhibition. This is what Display Week is all about! I tip my hat to Samsung for its bold demonstration and to everyone else who brought with them the good stuff!

Amid all the polished product demonstrations, you could find some other risky and early-stage demos of great concepts and technology. These developments may still have some work due them, but at least their stewards felt safe showing them off. Maybe this is why, as the exhibition has matured, we've seen such enthusiasm for the I-Zone, where edgy and early stage are the requirements. Everything you see there is based on sheer innovation, and far more human capital than cash is invested in keeping the project alive.

Flexible and conformable capability is what our current issue of *ID* is all about. Guest Editor Ruiqing (Ray) Ma has done a great job developing a trio of Frontline Technology articles for us that represent the latest thinking and state of the art for stretchable displays. I recommend you read his excellent guest editorial first to get his perspective on the lineup in this issue. Some of the work in these articles builds on folding-display capabilities already demonstrated, and yet most of us have not seen these foldable products in the marketplace today. We're still in the very early dawn of truly flexible and foldable products. I think this has to do, at least in part, with making them suitably robust and able to survive not only bending but true stress and strain as well. And so, this issue provides the next steps toward the goal of true folding, bending, and conforming display-based products.

Authors Yongtaek Hong and colleagues at Seoul National University start us off with their very thorough survey of the many ways that researchers are currently pursuing truly conformable substrates and display structures in their Frontline Technology article, "Stretchable Displays: From Concept Toward Reality." Included in this story is a mention and picture (Fig. 2) of the Samsung demo I referred to. If you did not have a chance to see it at the show at least you can see it here.

In "Stretchable Oxide TFT for Wearable Electronics," authors Xiuling Li and Jin Jang tell us about a very novel concept for making an active switching backplane by selectively ruggedizing small islands on an otherwise stretchable substrate called polydimethylsiloxane (PDMS). When oxide TFTs are attached to the small islands on the PDMS, they remain safe from stress/strain while the overall structure becomes highly conformable. I think this is a very promising method for further development.

(continued on page 37)

Information DISPLAY

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

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

Global Advertising Director:
Stephen Jezzard, sjezzard@wiley.com

Senior Account Manager Print & E-Advertising:
Roland Espinosa
201/748-6819, respinosa@wiley.com

New Products Arrive with the Warm Weather

A number of new products were introduced in May and June, including E Ink-based devices and the latest round of Apple tablets. Here is a look at several of them.

E Ink introduces New Prism Colors

E Ink recently announced the launch of seven new colors for E Ink Prism, its color-changing film for architecture and design. E Ink Prism utilizes the same bi-stable ink technology used in e-readers, wearables, and shelf labels, but includes color pigments in larger size films for use in architecture and design.

Fig. 1: *The seven new colors available for E Ink Prism increase options for designers of low-power, reflective signage and architectural elements.*

The colors are named, somewhat whimsically, voyage (dark blue), daydream (cyan), blush (red), sprout (green), zest (yellow), harvest (brown), and waltz (black).

While this isn't the technology that will bring us the color e-reader of our dreams, it can be custom programmed to create striking signage that switches colors in nearly any pattern, shape, and sequence (Fig. 1). E Ink describes the product as having a paint-like appearance and stresses its compatibility and customization readiness with materials such as decorative panels, glass, marker boards, and laminates.

QuirkLogic to Ship E Ink-Based Whiteboard in July

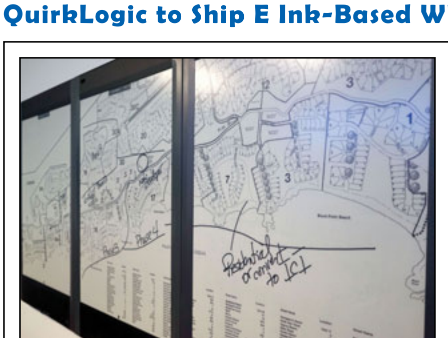


Fig. 2: *Quilla is a low-power, reflective, digital collaboration tool that offers users a look and feel similar to that of pen on paper.*

Canadian company QuirkLogic recently announced that its digital whiteboard product, which it describes as "a real-time ideation solution," would be available to the general public in mid-summer. The E Ink-based device, Quilla, enables remote workers and teams in multiple locations to create and collaborate by formulating, capturing, and sharing content in real time (Fig. 2).

Quilla was announced in January 2017 at the Consumer Electronics Show in Las Vegas, where it earned awards from both *ZDNet* and *TechCrunch*. Core to the product are its E Ink electronic paper display (EPD) and electronic ink technologies, which provide a simple, familiar interface for brainstorming and collaborating – similar to pen on paper. Quilla consumes little power and is readable under direct sunlight. The 42-in. display weighs only 22 pounds and operates for up to 16 hours on a single battery charge.

Apple Announces New Tablets

Apple recently introduced new 10.5-in. and 12.9-in. iPad Pros featuring "ProMotion" technology and the new A10X Fusion chip. The tablets' redesigned Retina display has an anti-reflective coating that makes content easier to see indoors and out. True Tone technology dynamically adjusts the white balance of the display to match the light around the user for a more natural and accurate viewing experience. In addition, Apple Pencil works more fluidly with the new tablets (Fig. 3).

Fig. 3: *Apple Pencil users may appreciate the enhanced fluidity offered by the new iPad Pros.*

ProMotion is a new technology that delivers refresh rates of up to 120 Hz for fluid scrolling, greater responsiveness, and smoother motion content. ProMotion also improves display quality and reduces power consumption by automatically adjusting the display refresh rate to match the movement of the content.

Fujitsu Launches Customizable Touch Panels for Industrial Machine Controls

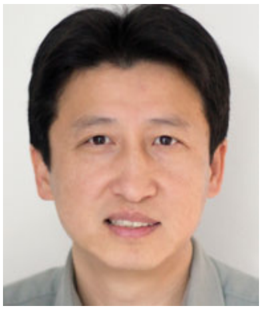
At Display Week 2017 in May, Fujitsu Components America unveiled a new series of resistive touch panels with dome switches designed for industrial automation and machine control applications.

The FID-11x series touch panels are composed of a film-glass sensor with a flush-surface film overlay that is dustproof, waterproof, and easy to clean. They are available in sizes up to 22 inches diagonal, feature 80 percent (typical) transparency, and have an operating life of 1 million taps.

To meet the demands of most industrial environments, the FID-11x series has a standard operating temperature range of –5° to +60°C and 3H pencil hardness. User input can be performed with a variety of implements, including a gloved finger. Available options include an

(continued on page 39)

guest editorial



Stretch of Imagination

by Ruiqing (Ray) Ma

I don't know about you, but every day before I sit down at work, I reach into my pocket, take out my phone, and put it on my desk. These devices are so big and rigid nowadays, they no longer fit comfortably in a pocket when you're sitting down. It is frustrating that we still don't have a truly flexible and conformal device, even though displays with these capabilities were developed a long time ago in the lab. In fact, the display community has already moved on to the next frontier of flexible displays – stretchable. In this special issue of *Information Display*, we have prepared three excellent articles to report the latest developments in the field of stretchable and wearable display technology.

To electronically address a stretchable display, either a stretchable electrode or a stretchable interconnect must be developed. Professor Hong and his colleagues provide an overview of the status of stretchable displays in their article, "Stretchable Displays: From Concept Toward Reality." To make a display itself stretchable, one method is to make every layer of the display stretchable, including the electrodes. Another is to make the display so thin that it can be pre-wrinkled into a much smaller area, making stretching possible later. For a high-information-content display with high-density pixels, one practical approach is to make a hybrid structure – leaving the active display pixel alone and having the interconnect take on the large strain during stretching. One can imagine making such a hybrid system is extremely challenging. You will be impressed by what the researchers have achieved – a fully printed, soft, platform-based passive-matrix LED display capable of withstanding 30 percent biaxial tensile strain.

In the article, "Stretchable Oxide TFT for Wearable Electronics," Dr. Li and Professor Jin Jang report their latest results on stretchable oxide TFTs. First, they developed an ultra-thin oxide TFT between two 1.5-µm polyimide (PI) substrates. Because they are placed in a neutral plane, these TFTs are super flexible – operational even after bending 20,000 times to a radius of 0.25 mm. These TFTs were then transferred onto pre-treated islands of polydimethylsiloxane (PDMS) stretchable substrate. Due to UV/O_3 treatment, these islands are relatively rigid, providing necessary protection for the TFT during stretching. With a mobility of ~14 cm^2/Vs, these TFTs showed less than 8 percent change during repeated stretching up to 50 percent strain, which is a remarkable achievement. With further optimization and improvement, this technology could offer exciting opportunities in wearable and stretchable electronics.

The last article takes a novel approach from the liquid-crystal level. We all know why we don't have a truly flexible device yet – the display doesn't exist by itself. There are so many other components in the device that are rigid and that also need to be made flexible. However, there may be a simple solution for this – getting rid of those components. In the article, "Developing Liquid-Crystal Functionalized Fabrics for Wearable Sensors," Dr. Junren Wang and his colleagues describe the development of a simple device – a passive sensor using liquid crystal (LC). The flexibility and stretchability are elegantly addressed by the structural arrangement of fibers – the basic component in fabrics and textiles. In addition, liquid crystals, such as short-pitch cholesteric, smectic C, and blue phase, are perfect visual sensing materials, as they respond through color change to a wide variety of stimuli such as temperature,

(continued on page 37)

Stretchable Displays: From Concept Toward Reality

Stretchable displays are now being developed using strategies involving intrinsically stretchable devices, wrinkled ultra-thin devices, and hybrid-type devices.

by Yongtaek Hong, Byeongmoon Lee, Eunho Oh, and Junghwan Byun

In the future, we may be able to remove a small display from our pocket and stretch it to create a larger screen, like something that would happen in a Hollywood movie. It seems exciting! If we want to do this with state-of-the-art, high-information (a few hundred ppi resolution) displays today and in the near future, we may find it very difficult. However, if we start with a low-resolution (maybe around 100 ppi) display and add a small percentage of stretching functionality, we might have more freedom in terms of form factor and various creative applications. Such a display could be attached conformably to any artistically designed, curved surfaces, even those with different curvatures in several directions, such as the inner or outer surfaces of vehicles, furniture, utensils, houses, and buildings.

In fact, these kinds of advanced-form-factor information displays have already been implemented through flexible display technology, going back more than 40 years. In 1974, Xerox Palo Alto Research Center (PARC) demonstrated the first flexible e-paper display, which could be flexed like paper while displaying digital images.[1] In 2005, nearly 30 years after that, Arizona State University opened the Flexible Display Center for development of flexible e-paper, and with support from HP, developed a prototype for an advanced flexible e-paper display in 2010. A few years later, this research then entered a new era with the development of flexible OLEDs. Nokia announced a concept mobile phone that used a flexible OLED display in 2008[2] and Sony demonstrated a 4.1-in. rollable OLED display in 2010.[3] In recent years, many companies have demonstrated paper-thin, flexible OLED displays.[3,4] Notably, Samsung Display Company and LG Display introduced curved-edge smartphones and curved televisions to the market[5,6] respectively, both of which are based on flexible OLED display technology.

Deformable and stretchable displays are the next-generation technology step beyond the above-mentioned curved, bendable, and foldable displays. During Display Week 2017, Samsung demonstrated a 9.1-in. stretchable active-matrix OLED (AMOLED) display, which won a Best in Show award from the Society for Information Display.[7] It is known that this display uses the so-called Kirigami-based stretchable technology,[8] which involves cutting or making holes in a thin sheet in order to make it stretchable. The ensuing net or mesh-type structure enhances stretching functionality, as shown in Fig. 1. Figure 2 is an example of concave and convex displays based on this type of stretchable technology.[7]

In order to further improve stretching functionality and fabrication processes for higher-resolution displays, a few recently reported strategies for stretchable displays can potentially be adopted. These include making devices that are intrinsically stretchable,

Yongtaek Hong, Byeongmoon Lee, Eunho Oh, *and* ***Junghwan Byun*** *are with Seoul National University. Hong can be reached at yongtaek@snu.ac.kr.*

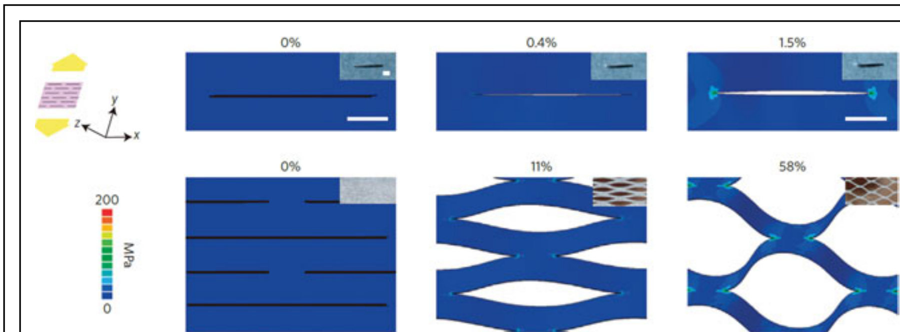


Fig. 1: *The stress distribution for Kirigami structures is determined here by finite element method (FEM) analysis.[8]*

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creating an entire system that is extremely thin and "wrinkled," and engineering strain distribution for rigid-soft hybrid integration. Details of these strategies are described in the next section by focusing on stretchable light-emitting devices.

Technical Details

Intrinsically stretchable thin-film devices typically involve new conductor, insulator, and semiconductor materials or mechanically robust novel structures, which help provide stable operation for the fabricated devices, even under harsh tensile stress conditions. Stretchable electrodes have been implemented via wrinkled metal thin films,[9] horseshoe-shaped silicon ribbons,[10] and liquid-metal channels.[11] Facile fabrication of fine feature patterns and integration into high-resolution array formats remain among the technical challenges, while such electrodes show excellent conductive property and mechanical robustness when implemented in relatively large feature size. For stretchable thin-film transistors (TFTs), mechanically durable materials such as semiconductor single-walled carbon nanotubes (SWCNTs)[12] and organic semiconductors[13] have been widely exploited for active layers with ion gel[14] or elastomeric dielectric materials.[15]

Although whole devices based on the above technologies can be stretchable, their performance is typically lower than that of TFTs employed in current commercial products and their fabrication process is not yet compatible with typical display fabrication processes. However, there have been tremendous efforts toward overcoming such technical challenges, and fundamental frameworks to implement stretchable display systems have begun to be established. The bulk of these methodological efforts can be described in detail on the basis of three approaches: (1) intrinsically stretchable light-emitting devices, (2) wrinkling, ultra-thin, light-emitting devices, (3) hybrid stretchable devices integrated with stretchable electrodes.

Intrinsically Stretchable Light-Emitting Devices

One of the key technologies of stretchable, light-emitting devices is the stretchable transparent electrode, which has been typically implemented by composite-based or organic transparent conductors.[16,17] The lower conductivity of those conductors has made the performance of light-emitting devices poor in comparison to those with conventional indium tin oxide (ITO) electrodes. Their operational stability is inferior, although they show excellent mechanical robustness. Furthermore, technical challenges in the fine-feature patterning of such transparent electrodes has limited their application to unit devices with polymer[16,18] light-emitting diodes (PLEDs). In addition, multi layer based light-emitting devices may not be a good candidate due to their mechanically fragile or vulnerable interfaces with the stretchable elastomer substrate. Therefore, most recently, easily deformable gel-based electrodes and an elastomer-compatible phosphor – especially zinc sulfide (ZnS) – have been widely used to fabricate highly stretchable electroluminescent (EL) devices.

In 2016, Professor Zhigang Suo and co-workers at Harvard University demonstrated extremely stretchable light-emitting devices composed of transparent ionic conductors and ZnS phosphor particles.[19] They sandwiched phosphor particles between two layers of dielectric and ionic conductors, both of which were transparent and stretchable. The inserted phosphor particles did not compromise the stretching function of either layer. These intrinsically stretchable light-emitting devices were able to withstand a tensile strain of 1,500 percent without losing their light-emitting ability [Fig. 3(a)]. In addition, Professor Robert Shepherd and co-workers at Cornell University reported highly stretchable electroluminescent devices made with elastomer and ZnS composites.[20] These can be stretched up to nearly 400 percent. The Cornell team demonstrated multi-pixel electroluminescent displays fabricated via replica molding [Fig. 3(b)].

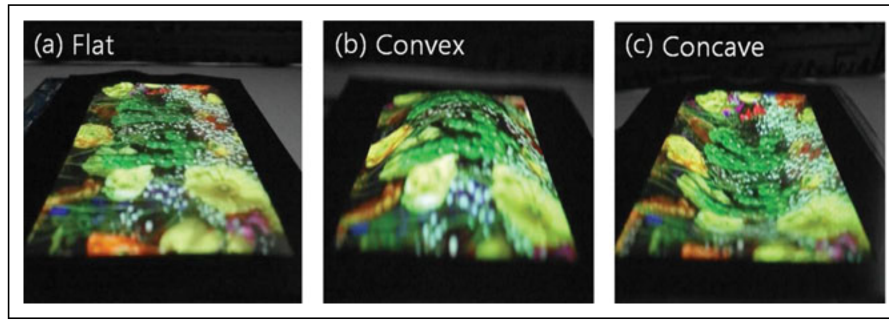

Fig. 2: *These photographs of a fabricated AMOLED prototype include (a) an un-deformed shape, and (b) and (c) convex and concave shapes produced through thermoforming processes.*[7]

Despite these excellent achievements, there are still considerable technical issues to be addressed in terms of the practical implementation of intrinsically stretchable light-emitting devices. Because most of the intrinsically stretchable electronic components are based on the composite materials of functional filler and elastomeric matrices, they suffer from low performance and high-bias voltage. In addition, this approach has difficulty in patterning the light-emitting devices into a small pixel and integrating with the backplane for stretchable high-resolution display applications.

Ultra-Thin Light-Emitting Devices

As mentioned in the previous section, it might be difficult to fabricate OLEDs directly onto the surface of elastomeric materials, which typically have low surface energy and thus, poor adhesion property. However, if a device or system with multi layer structures is fabricated on a more favorable surface of significantly reduced thickness, it can then be transferred onto an elastomeric substrate. Buckling features can then be added to the whole system. Ultra-thin devices typically show mechanically peculiar characteristics compared to bulky ones. In general, inorganic layers in multi layer devices are vulnerable to bending in a small curvature due to brittleness or large Young's modulus. On the other hand, if the whole device can be made into an ultra-thin foil with a few micrometers, the applicable bending radius can be reduced to even 10 um, allowing it to conformably contact any arbitrary-shaped surfaces.

In 2016, Professor Someya's group at the University of Tokyo demonstrated ultra-thin and highly efficient PLEDs on a 1-um-thick

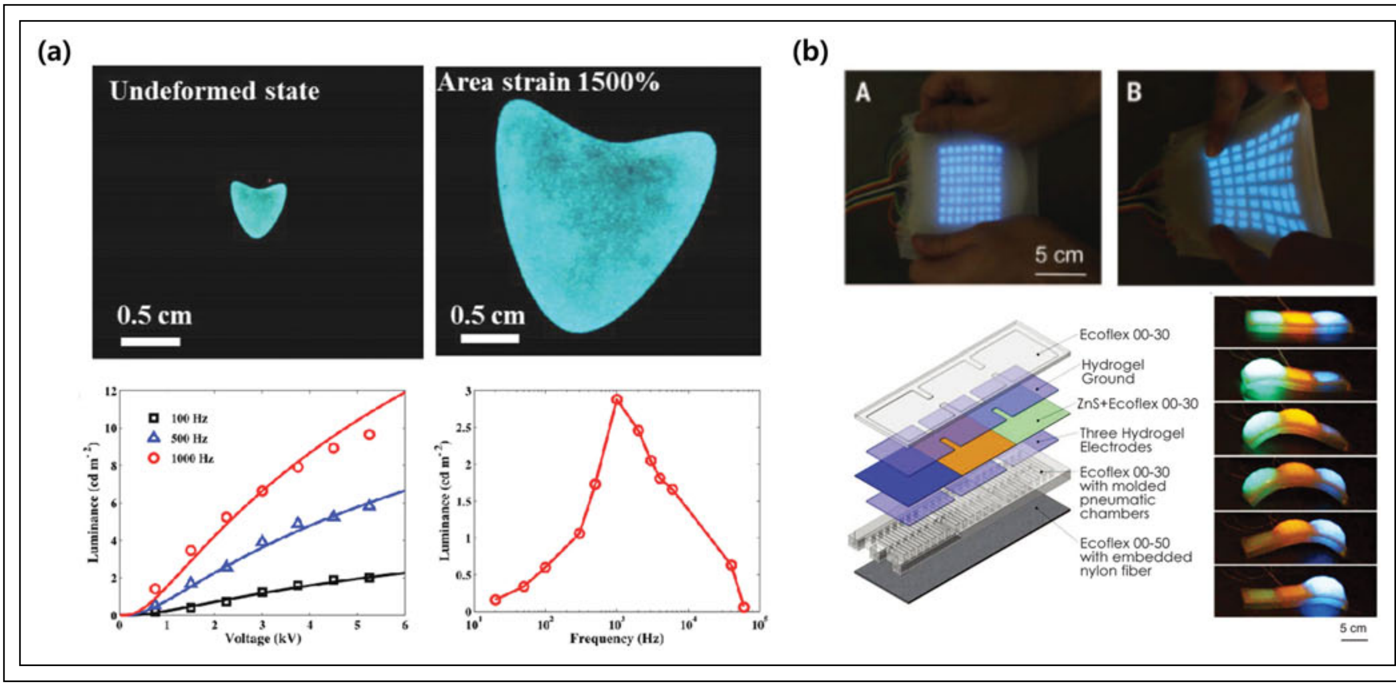

Fig. 3: Electroluminescent devices with ionic gel conductors and ZnS phosphors depicted here include (a) extremely stretchable light-emitting devices composed of transparent ionic conductors and ZnS phosphor particles[19] and (b) highly stretchable electroluminescent devices made with elastomer and ZnS composites.[20]

parylene substrate (Fig. 4).[21] Owing to a reduction in the total thickness to 3 um and positioning active layers on the neutral strain plane, multi layered PLED and even brittle ITO transparent conductors can withstand harsh bending conditions (bending radius ~ 100 um). Also, the existence of a flexible passivation layer with a multi layer structure of silicon oxynitride (SiON) and Parylene (a chemical vapor deposited poly(p-xylylene) polymer), greatly increased the half lifetime of the device from 2 to 29 hours. Interestingly, such ultra-thin foil-based devices can easily become stretchable when laminated onto a pre-stretched elastomeric substrate, such as an acrylic tape-silicone rubber sheet.

After release, wrinkled structures were formed on the laminated ultra-thin devices due to the modulus difference of each layer. These wrinkled structures act as a mechanical buffer, allowing the laminated device to be stretched with minimal change in performance when a large strain is applied to the substrate. The fabricated stretchable lighting device showed no degradation under repetitive 60% stretching (1,000 cycles). Although this ultra-thin foil strategy also shows excellent performance, there are still technical challenges

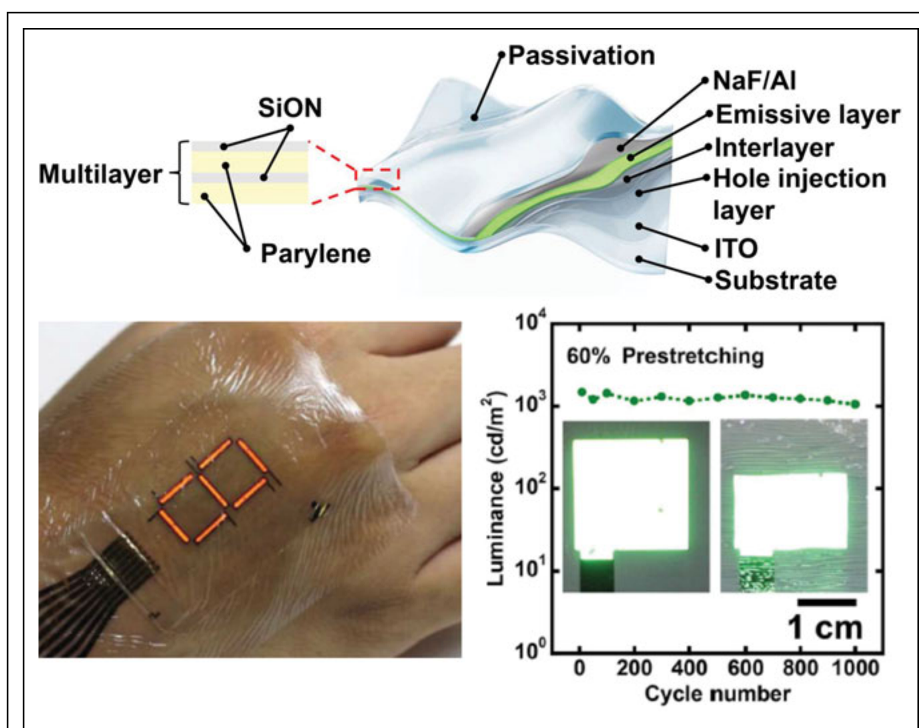

Fig. 4: An ultrathin PLED device is outlined at top, with its stretchable application shown at lower left and results at right.[21]

for high-resolution, stretchable active-matrix display applications. This is due to the thickness of the entire display layer – including light-emitting device, TFT backplane, and passivation/encapsulation layer – which must be reduced to a few micrometers, while the same operation property and lifetime must be guaranteed even under stretching stress conditions.

Stretchable Hybrid Display Based on Inorganic LEDs

As an alternative strategy, many research groups have demonstrated stretchable hybrid displays, in which the conventional inorganic LEDs (iLEDs) are interconnected by stretchable electrodes.[22] Since iLEDs in die or packaged form are mass-produced by conventional semiconductor processes, if an appropriate integration method is developed for making high-resolution displays, this approach can be one of the key technologies for stretchable display implementation in a facile manner. The intrinsic rigidity of iLEDs, however, often causes severe failure – mainly at the interface between rigid chips and soft materials – due to modulus mismatch under tensile strain conditions. Therefore, in order to utilize this hybrid strategy, it is necessary to selectively manage stress distribution over the whole system.

In 2010, Professor John A. Rogers and co-workers demonstrated a micro-inorganic light-emitting diode (μ-iLED) and photodetector array with mechanically designed layouts [Fig. 5(a)].[22] μ-iLEDs and interconnects were fabricated on the polyimide (PI) ribbons by using conventional patterning methods such as etching and mask-assisted deposition processes. The μ-iLEDs with the interconnects were then transfer-printed onto a pre-stretched elastomer substrate. Since the iLEDs were firmly adhered to the substrate, they acted as well-defined islands, which were connected by the serpentine interconnects that were slightly floated in an out-of-plane direction. Such a structure allowed the researchers to demonstrate an μ-iLED array composed of 6 × 6 iLEDs with a stretchable function of nearly 50%.

Due to facile and scalable properties, the integration of iLEDs into a stretchable array format has attracted commercial interest, mainly in low-resolution dot-matrix displays. In 2015, researchers at Holst Centre and CMST, associated with IMEC, developed a stretchable 45 × 80 RGB iLED display with meander interconnects and rigid island strategy [Fig. 5(b)].[23] Thirty-six-hundred RGB iLEDs were placed at strain-relief rigid islands, which provided mechanically stable protection for the contacts between chips and interconnects. In addition, having the meander interconnects embedded in a polyurethane film allows this small pixel-pitch (3 mm) display to show excellent performance, with a stretchable function of up to 10%.

Since the number of meandering or serpentine structures is directly related to the stretchability of the interconnects, such lateral stretchable structures can limit potential increase in display resolution. If buckling

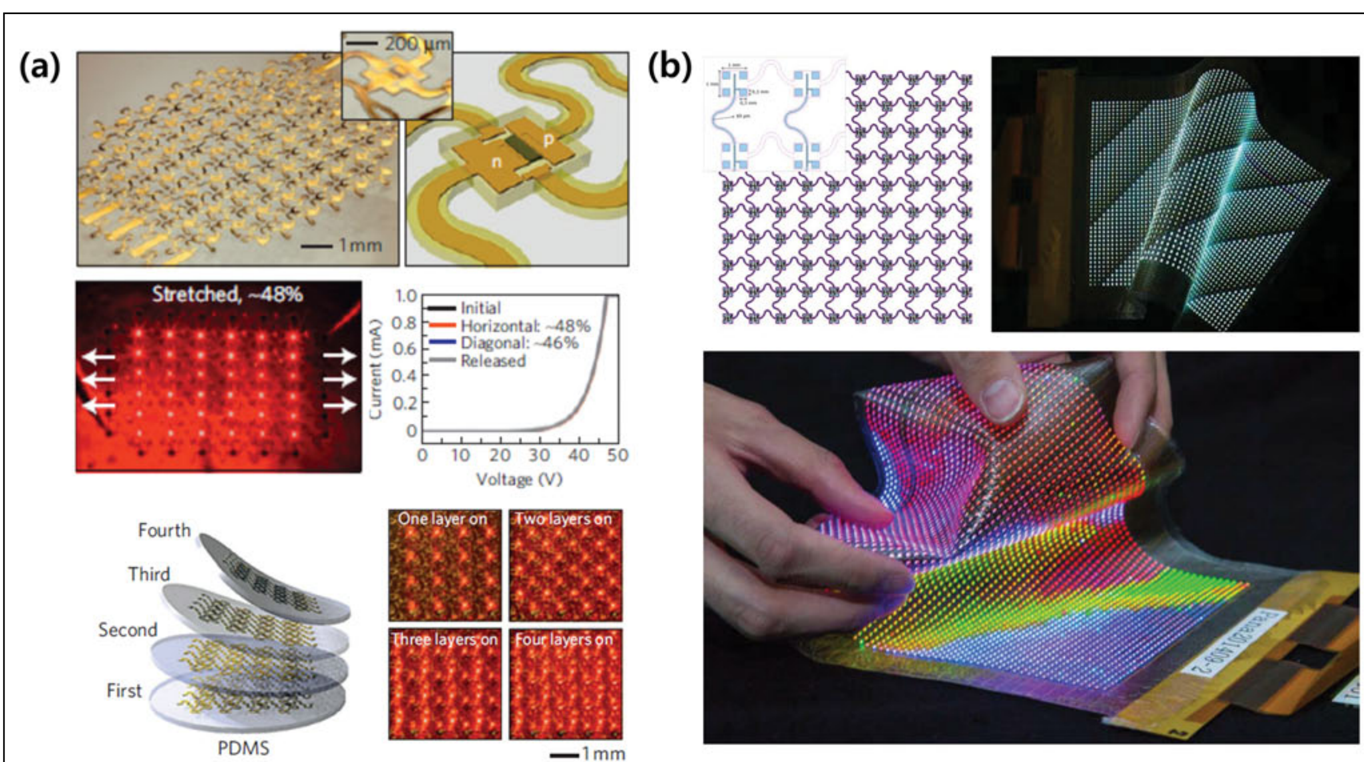

Fig. 5: These examples of stretchable hybrid display technology using iLEDs include (a) a micro-inorganic light-emitting diode (μ-iLED) and photodetector array with mechanically optimized layout[22] and (b) a stretchable 45 × 80 RGB iLED display with meander interconnects.[23]

electrodes can be combined with the island and interconnect strategy in a facile manner, display resolution can be further improved. In addition, it is important to develop a fabrication process to obtain the patterned buckling electrodes directly on the stretchable substrate. In 2017, Professor Hong's group reported a fully printable, strain-engineered soft platform for customizable wearable systems including passive-matrix iLED displays.[24]

Figure 6 shows the key concept involving the strain-engineered stretchable platform implemented by embedding inkjet-printed rigid islands (PRIs) into the soft matrix and inkjet-printing stretchable interconnects between the islands. Since the printing processes can be used for PRI formation, universal or customized PRI arrays can be easily implemented. On a rigid glass substrate, a sacrificial layer and a thin PDMS layer are spin-coated. After curing both layers, PRIs are inkjet-printed in various forms. After relatively thick PDMS layers are coated and cured, the PRI-embedded PDMS layer is detached from the glass substrate.

Figure 6(a) shows a comparison between typical and stretchable universal PCBs. They are conceptually similar, in that, for a given universal PRI array, we can freely choose the target PRIs for chip placement according to to-be-implemented electronic systems. In addition, we can pre-design the PRI array for chip placement instead of using the universal format, as shown in Fig. 6(b). In order to provide more freedom on routing topology, we also developed a program that can produce image files for various interconnects according to the user's intention. The image files are uploaded onto the printer, so that the inkjet-printer can draw the interconnects between the selected PRIs.

Figure 6(b) shows examples of various topologies for the interconnects of a given PRI array. Since the printing process is performed on the pre-strained PRI-embedded PDMS substrate, two-dimensional wrinkles are formed after curing the printed Ag electrode, followed by releasing the applied pre-strain, as shown in Fig. 6(b). A magnified image of the Ag electrode with two-dimensional wrinkles is shown in Fig. 7(a).

Figure 7 shows a stretchable hybrid 5 × 7 iLED array display implemented on a PRI-embedded platform. Since iLEDs and their bonding areas are located on each PRI, any applied external strain is effectively absorbed by the wrinkled electrodes. The tensile strain on the rigid island areas is kept low enough to protect the mounted iLEDs, even under a large biaxial tensile strain. Moreover, stable bonding between the iLEDs and the inkjet-printed stretchable electrodes is achieved by using pure and conductive epoxy materials. Due to optimized rigid island configuration and robust chip bonding, this stretchable passive matrix display showed great reliability under a biaxial tensile strain of 30% [Fig. 7(b)] and a great working stability in harsh environments [Fig. 7(c)]. All the processes from the inkjet printing of rigid islands to the bonding of iLEDs are sequentially performed in situ. It is also noted that in such an array form, it is necessary to fabricate crossovers at the cross-section area of vertical and horizontal interconnects. As shown in Fig. 7(a), the printed PDMS crossovers performed well and showed stable operations under various tensile stress conditions. Finally, the programmed microcontroller units that are directly mounted on the elastomeric substrate enabled the display to operate in a stand-alone mode without any extra wires for the data communications.

Although stretchable hybrid displays have several advantages, such as relatively high in-air stability, potentially low-cost process, and facile scalable integration, they have their limits in terms of realizing high-resolution information displays at this point. However, if the micro iLED transfer process is combined with the substrate engineering and correspondingly processed TFT backplane, stretchable hybrid displays should have a promising future for various high-resolution applications.

Challenges and Future Directions

Beginning with flexible e-paper displays, deformable displays have undergone numerous innovations and evolved into various forms, from curved to stretchable. Stretchable display prototypes have been developed using strategies of intrinsically stretchable devices, wrinkled ultra-thin devices, and hybrid-type devices. Although only low-resolution displays have been demonstrated up to now, there is potential in implementing high-resolution ones when the key enabling technologies developed for the stretchable displays are appropriately combined.

For example, in order to obtain operational stability and image quality with stretchable functionality as well, the active pixel area needs to be free from deformation under the

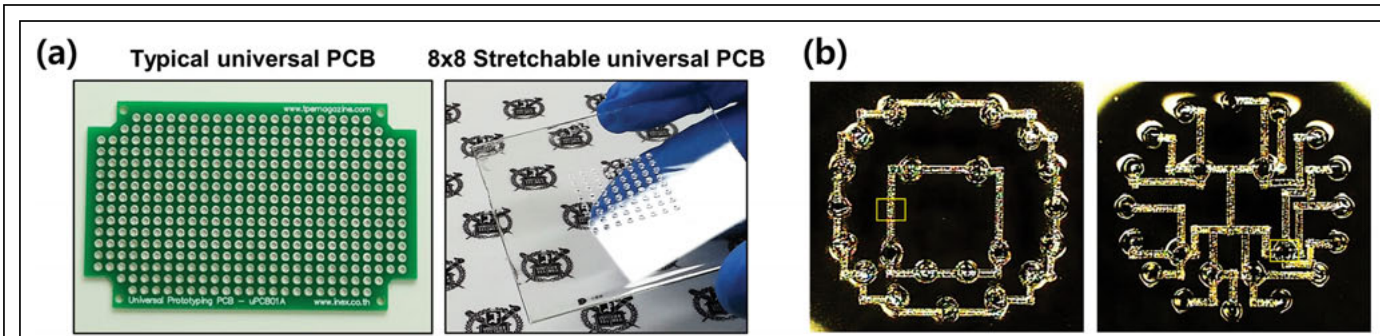

Fig. 6: The concept of stretchable universal/customized PCB platforms and various inkjet-printed routing topologies is represented in (a), by a comparison between typical and stretchable universal PCB concepts, and in (b), by two examples of inkjet-printed routing for a given customized PRI array. Custom-developed automatic routing programs enable change and optimization of the interconnect patterns.

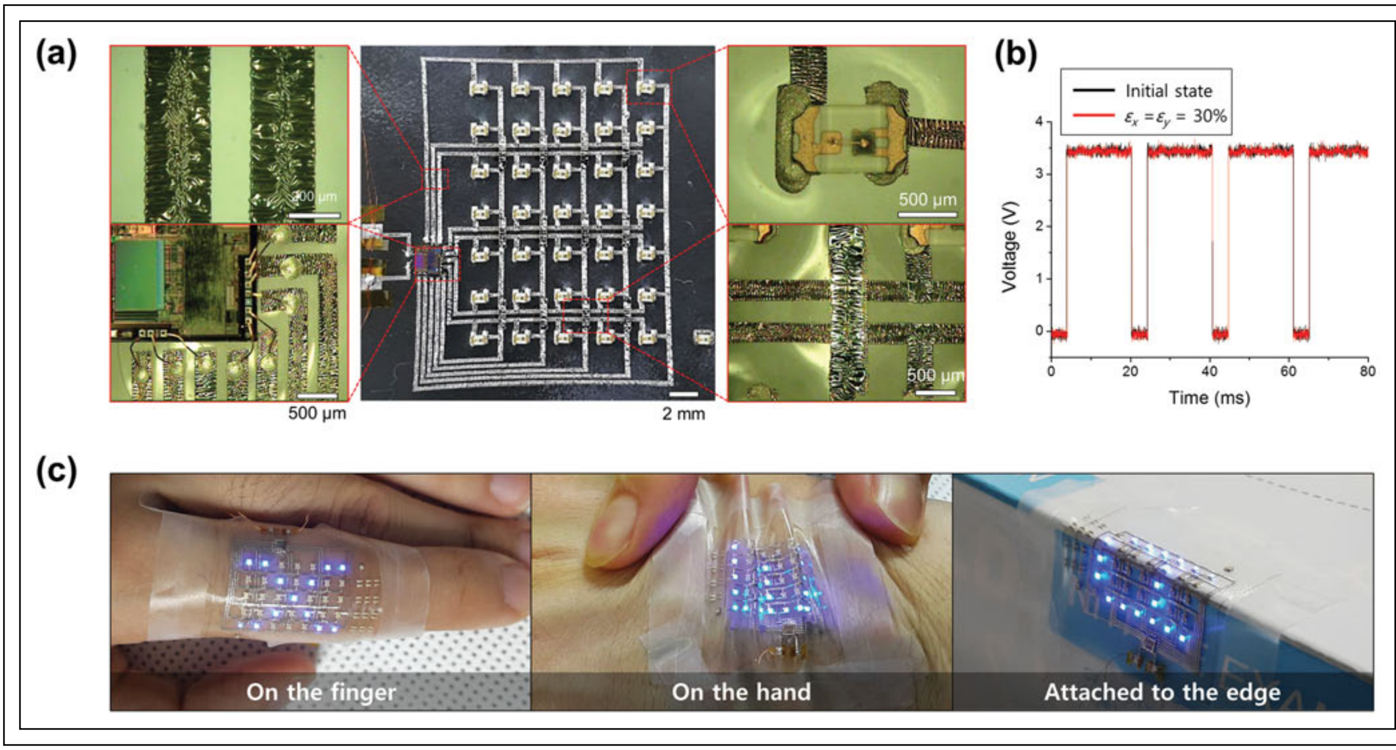

Fig. 7: *Stretchable hybrid iLED displays implemented on PRI-embedded skin-like elastomeric platforms are depicted and described as follows: (a) optical images of a stretchable passive-matrix display and its enabling technologies; (b) operating input signals of an iLED before and after deformation under 30% biaxial strain; and (c) photographs of the stretchable passive-matrix display operated under various conditions.*[24]

external tensile stress. In fact, the proper strain engineering strategy can be adopted by either thinning and wrinkling or controlling stress distribution. However, based on our previous research,[24] there is still some amount of strain (< 2%) in the pixel area even though the optimized strain engineering is used. Therefore, somewhat intrinsically stretchable devices need to be adopted for stretchable high-resolution displays. In addition, stretchable passivation and encapsulation layers are among the biggest challenges for stretchable OLED displays. If other light-emitting devices, such as iLEDs, which are stable in air, can be used, the requirement of gas permeation of the layers is less demanding, and stretchable passivation and encapsulation layers can thus be implemented more easily.

There is no doubt that we will see early commercialization of stretchable low-resolution displays or stretchable wearable patch devices based on a combination of the aforementioned three strategies. Hollywood makes people dream, and the Society for Information Display makes those dreams come true!

References

[1]I. Genuth, "The Future of Electronic Paper," *The Future of Things*, http://thefutureofthings.com/3081-the-future-of-electronic-paper
[2]Nokia Research Center, "The Morph Concept," Nokia, 2008.
[3]T. Ricker, "Sony's rollable OLED display can wrap around a pencil, our hearts," *Engadget*, www.engadget.com/2010/05/26/sonys-rollable-oled-display-can-wrap-around-a-pencil-our-heart
[4]B. Crew, "LG Unveils Its New Flexible, Paper-Thin TV," *Science Alert*, www.sciencealert.com/lg-unveils-its-new-flexible-paper-thin-tv
[5]S. Byford, "Samsung's Galaxy Round is the first phone with a curved display," *The Verge*, www.the verge.com/2013/10/8/4818572/samsung-galaxy-round-curved-oled-smart-phone-official
[6]D. Pierce, "Battle of the curved OLED TVs: LG matches Samsung with its own 'world's first,' " *The Verge*, www.theverge.com/2013/1/8/3852438/battle-of-the-curved-oled-tvs-lg-matches-samsung-oled-curved-tv
[7]J.-H. Hong, J. M. Shin, G. M. Kim, H. Joo, G. S. Park, *et al.*, "9.1-inch stretchable AMOLED display based on LTPS technology," *JSID,* 2017.
[8]T. C. Shyu, P. F. Damasceno, P. M. Dodd, A. Lamoureux, L. Xu, *et al.*, "A kirigami approach to engineering elasticity in nanocomposites through patterned defects," *Nature Materials* **14**, 785–789, 2015.
[9]D.-Y. Khang, J. A. Rogers, and H. H. Lee, "Mechanical Buckling: Mechanics, Metrology, and Stretchable Electronics," *Advanced Materials* **19**, 1526–1536, 2009.
[10]S. Xu, Y. Zhang, J. Cho, J. Lee, X. Huang, *et al.*, "Stretchable batteries with self-similar serpentine interconnects and integrated wireless recharging systems," *Nature Communications* **4**, 1543, 2013.
[11]J. W. Boley, E. L. White, G. T.-C. Chiu, and R. K. Kramer, "Direct Writing of Gallium-Indium Alloy for Stretchable Electronics," *Advanced Functional Materials* **24**, 3501–3507, 2014.
[12]J. Liang, L. Li, D. Chen, T. Hajagos, Z. Ren, *et al.*, "Intrinsically stretchable and transparent thin-film transistors based on printable silver

(continued on page 38)

Stretchable Oxide TFT for Wearable Electronics

Oxide thin-film transistors (TFTs) in a neutral plane are shown to be robust under mechanical bending and thus can also be suitable for TFT backplanes for stretchable electronics. The oxide TFTs when built on a PI substrate can then be transferred onto a PDMS substrate and applied to stretchable electronics. The PDMS regions on the TFT parts are UV/O_3 treated for stiff PDMS and then the TFTs are transferred onto this region. This substrate with TFTs applied can then be stretched up to 50 percent without significant performance degradation. Therefore, stretchable oxide TFT arrays can be used for stretchable displays and sensors.

by Xiuling Li and Jin Jang

Stretchable electronics can enable innovative applications such as electronic textiles, wearable displays, and sensors. One of the key challenges of this technology is to design a device/system that tolerates high levels of strain (>>1 percent) without degradation of performance. This challenge entails numerous research issues covering a broad range of fields, including materials, device architectures, mechanics, and fabrication methods.[1]

***Xiuling Li** received her MS degree in information display engineering from Kyung Hee University, Seoul, Korea, in 2014, where she is currently pursuing a Ph.D. in information display technology. Her current research interests include thin-film transistors and circuits for use in display applications.*
***Jin Jang** received a Ph.D. in physics from the Korea Advanced Institute of Science and Technology. He is currently a director of the Advanced Display Research Center in Kyung Hee University, Seoul, Korea. His current interests include flexible and stretchable electronics using oxide and LTPS TFTs. He can be reached at jjang@khu.ac.kr.*

A stretchable thin-film transistor (TFT) is a basic building block for electronic circuits, displays, and sensors. Table 1 presents a brief summary of stretchable TFTs reported in the literature. Although mechanically robust materials and components have been improved recently, fabrication processes with high yield and device stability under mechanical strain remain challenging issues in terms of commercialization.[2–6] Of note are some efforts in ruggedization of devices that show excellent performance but less "softness." Wavy, coiled, net-shaped, or spring-like structures have also been used to accommodate large mechanical deformations.[7–10] In addition, active devices on stiff islands that are interconnected with stretchable conductors have proven successful in achieving highly stretchable electronics.[10–14]

Table 1. Stretchable TFTs for integrated circuits, displays, and sensors

Semiconductor	Insulator	Electrode	Approach	Stretchability	Mobility (cm^2/Vs)	Electronics	Ref.
Graphene	Ion gel	PEDOT:PSS	Intrinsically stretchable	5%	26	TFT array	2
SWCNT	PDMS	M-SWCNT	Intrinsically stretchable	22.5%	24	TFT array	3
SWCNT	PU-co-PEG	AgNW-PU	Intrinsically stretchable	50%	27	AMOLED	4
SWCNT	PU	PEDOT:PSS/PU	Intrinsically stretchable	70%	/	Thermal & strain sensor	5
DPP-polymer	PDMS	VNT/PEDOT:PSS	Intrinsically stretchable	100%	0.3	TFT array	6
CNT	Ion gel	Cr/Au	Buckling	60%	10	TFT array	7
SWCNT	Al_2O_3	G/CNTs	Wrinkled G.I.	20%	40	TFT array	8
ZnO	SiO_2	ITO	Wavy structure	5%	1.2	TFT array	9
IGZO	SiO_2	ITO	SU-8-encapsulated	5%	15	TFT array	11
IGZO	Al_xO_y/Parylene	Cr/Au	SU-8 stiff island	20%	2.6	TFT array	12
LTPS	/	/	Islands	5%	~100	AMOLED	13
IGZO	Al_2O_3	Ti/Au	Wavy structure; stiff patches	210% (wavy); 120% (stiff)	11.3	Amplifier	10

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Concurrently, oxide semiconductor TFTs, such as amorphous-indium-gallium-zinc-oxide (a-IGZO) TFTs, have drawn considerable attention due to their combined merits of high transparency, large field-effect mobility (>10 cm^2/V.s), good uniformity, and excellent electrical stability, even when deposited at room temperature.[15]

We have recently reported highly robust neutral plane (NP) a-IGZO TFTs that can undergo bending with a 0.25-mm radius. The combination of a thin substrate and TFTs located near the neutral bending plane results in highly stable oxide TFTs under mechanical strain.[16] The TFT can be in a neutral plane if there is no strain to it, even though it is bent. This is possible when it is in between two polyimide (PI) layers with the same thickness. In this article, we report on the integration of the neutral plane oxide TFTs onto selectively modified polydimethylsiloxane (PDMS) substrate material and evaluate the performance of the stretchable devices[16] resulting from this architecture. The PDMS substrate in this case was selectively treated by UV/O_3 to form a stiff silica-like layer in specific regions of the surface. These regions become rigid, while the untreated surrounding areas remain highly stretchable.[17] The oxide TFTs on the stiff regions, which you might think of as islands within a stretchable sea, can tolerate as much as 50 percent mechanical stretching of the surrounding substrate and still perform well after repeated stretching and relaxing. We attribute this advantage to the reduced strain on these hardened islands,[17] which in turn preserve the structural integrity of the TFTs. This technology provides a promising approach to wearable electronics using oxide TFT technology. It is based on papers recently published on NP a-IGZO TFTs[16] and stretchable TFTs.[18]

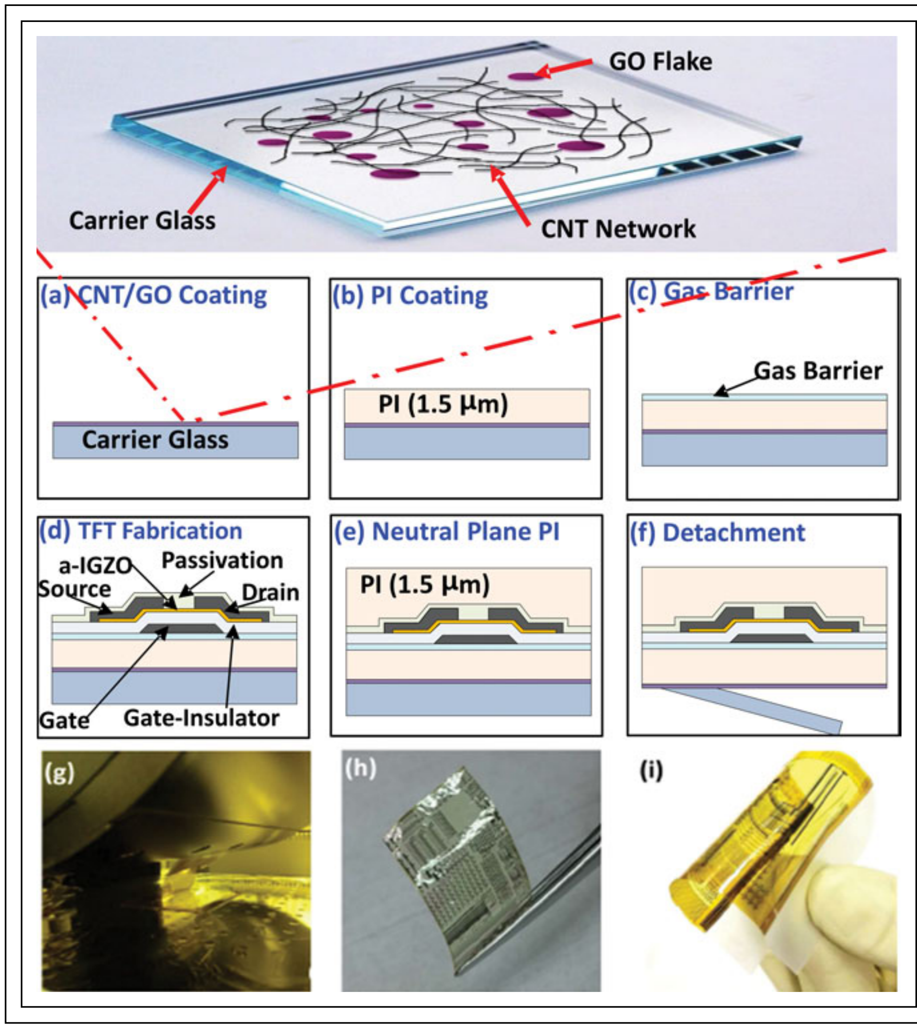

***Fig. 1:** The fabrication process flow of neutral-plane TFTs on a 1.5-μm PI substrate is shown above. See text below for explanations.*

Oxide TFTs on a Neutral Plane

The path to a stretchable backplane system begins with a very thin PI substrate selected for its extreme bending capability. On this substrate we fabricate a-IGZO TFTs. Once the TFT fabrication is complete, we deposit a second, very thin PI layer on top of the TFT devices to ensure that the devices are located close to the neutral bending plane between the two PI layers, for minimum strain exposure. As the resulting construction bends, the least amount of stress is experienced by the TFTs in the sandwich between the two PI layers. Also, a mixture of graphene oxide (GO) and carbon nanotubes (CNTs) is applied to the bottom surface of this substrate for mechanical support and reduction of electrostatic discharge (ESD) damage.

The process to create this architecture is illustrated in Fig. 1, beginning with the CNT/GO layer, which is first deposited by spin coating onto a carrier glass as illustrated in Fig. 1(a). In Fig. 1(b), we show the PI layer also being deposited by spin-coating onto the carrier. Next, the PI layer with CNT/GO is covered by SiO_2 and SiN_X as shown in Fig. 1(c). The purpose of this SiO_2 and SiN_X layer is to act as a gas barrier. The prepared PI substrate with gas barrier is now ready for TFT fabrication and that step is illustrated in Fig. 1(d). The second PI layer (1.5 μm) previously discussed is then deposited on top of the devices also using spin coating, as shown in Fig. 1(e). In Fig. 1(f), detachment of the complete stack-up from the carrier glass occurs using a detachment machine [Fig. 1(g)] resulting in the complete structure of a-IGZO TFTs fabricated on the PI substrate without [Fig. 1(h)] and with [Fig. 1(i)] the top PI layer. Once the structure is detached from the glass, it yields a freestanding flexible device. We produced a number (more than 10) of these devices with the goal of comparing the performance of devices with and without the top PI layer by performing prolonged mechanical stress tests under extreme bending conditions.

To evaluate the bending stability of the a-IGZO TFTs, the samples were wound onto a cylinder of decreasing radius and tested while bending. Starting from a cylinder with a radius of 3 mm all the way down to a cylinder with radius of 0.25 mm, devices with and without the top PI layer showed negligible changes in operation for all bending radii. Figure 2(a) shows an image of a sample wound to a cylinder of a radius of 0.25 mm.

The TFTs were then exposed to repeated bending cycles down to a radius of 0.25 mm using a special bending machine [Fig. 2(b)]. The placement of the sample on the bending machine was such that the direction of the bending stress was perpendicular to the TFT current flow. The TFTs without the top PI layer achieved up to 2,000 cycles before breaking down [Fig. 2(c)], while those with the top PI layer (resulting in an NP TFT structure) remained operational even after 20,000 cycles [Fig. 2(d)]. Clearly, this shows that the NP structure is superior for producing bendable a-IGZO TFT devices.

Stretchable Oxide TFTs

The next step in this investigation was to develop a stretchable system utilizing these NP oxide TFTs on PI substrate. We did this by cutting the NP oxide TFTs on PI substrate into small squares of 3 mm × 3 mm using a CO_2 laser. The squares were then transferred to specific regions of a PDMS substrate that had been previously treated by UV/O_3 to form a stiff, silica-like surface layer in those locations.

This process is shown below in Fig. 3 beginning with the TFT arrays on the PI substrate ready for laser cutting and transfer in Fig. 3(a). The preparation of the PDMS stretchable substrate as shown in Fig. 3(b) was achieved by spin-coating PDMS onto the carrier glass, followed by a subsequent baking cycle at 150 °C for 15 minutes. The stand-alone stretchable PDMS film was then separated by peeling it from the carrier glass.

To selectively modify its surface, the PDMS substrate was covered with a square-shaped photo-mask and then exposed to UV/O_3 for 2 hours. The mask pattern was 3 mm × 3 mm squares at intervals of 3 mm. The surface of PDMS in the regions exposed to UV/O_3 forms a thin, stiff, silica-like layer with a gradient depth profile, while the unexposed regions remain completely soft.[17] Finally, the island-shaped TFTs arrays cut from the PI substrate were transferred to the UV/O_3-treated PDMS regions. Figure 3(c) shows the optical micrograph of the NP oxide TFT arrays on UV/O_3-treated islands of the PDMS substrate.

Once this fabrication process was completed, we measured the relevant performance characteristics of the a-IGZO TFTs. Figures

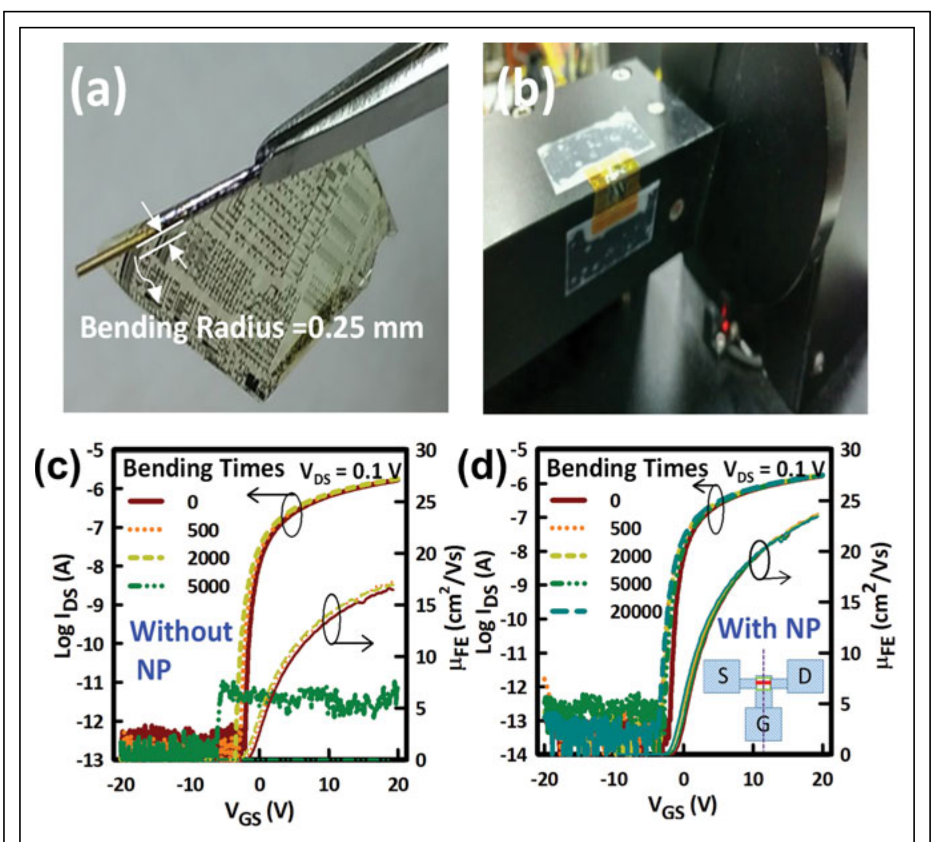

Fig. 2: In these bending test figures, (a) shows an optical micrograph of a sample wound on the cylinder with a radius of 0.25 mm; (b) is a photograph of the extreme bending machine; (c) shows transfer characteristics as a function of the bending cycle of a-IGZO TFTs without and (d), with, the top PI layer. All TFTs have a channel width (W) = 50 μm and a channel length (L) = 8 μm.[16]

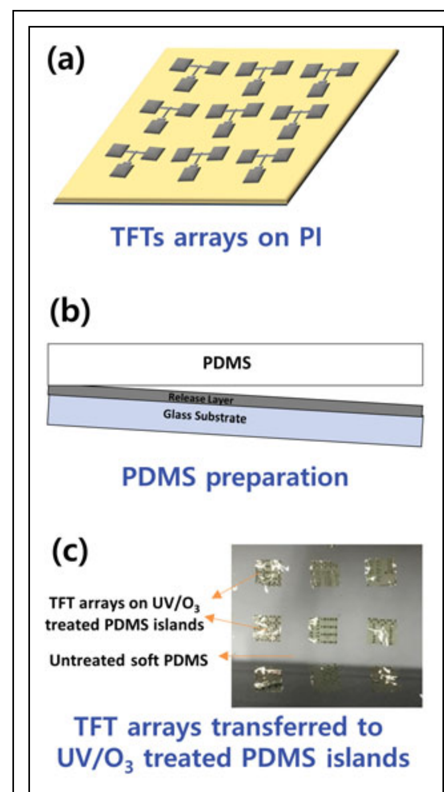

Fig. 3: The design concept for stretchable oxide TFTs includes (a) neutral-plane TFT arrays on PI substrates for cutting by a laser and transfer onto PDMS substrate; (b) spin coating and detachment of PDMS from release layer on glass; and (c) an optical image of TFT arrays on PDMS islands selectively treated by UV/O_3 (islands: 3 × 3 mm^2, intervals: 3 mm).[18]

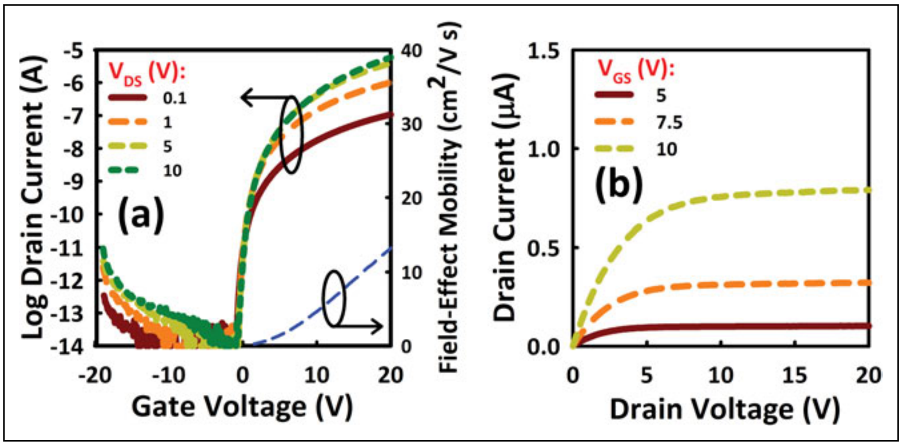

Fig. 4: Performance of oxide TFTs on the UV/O_3-modified region of the PDMS substrate is shown in (a) transfer and (b) output curves of a typical oxide TFT with W of 6 μm and L of 10 μm. The TFT exhibits a field-effect mobility of 13.8 cm^2/V.s, threshold voltage of ~0.1 V, and subthreshold swing of 0.18 V/dec.[18]

4(a) and 4(b) show the transfer and output characteristics respectively in the relaxed state after transfer onto a PDMS substrate with a channel width (W) of 6 μm and a channel length (L) of 10 μm. The devices exhibited a field-effect mobility (μ_{FE}) of 13.8 cm^2/V.s, turn-on voltage (V_{ON}) of 0.1 V, and subthreshold swing (SS) of 0.18 V/dec, indicating they had been successfully transferred onto the PDMS substrate. The field-effect mobility (μ_{FE}) is derived from the transconductance $g_M = \partial I_{DS}/\partial V_{GS}$, with V_{DS} = 0.1 V. V_{ON} is taken as the gate voltage (V_{GS}) at which I_{DS} starts to monotonically increase, and SS is taken as $(d \log (I_{DS})/d V_{GS})^{-1}$ of the range 10 pA $\leq I_{DS} \leq$ 100 pA, with V_{DS} = 0.1 V.

To evaluate the stretchability of this construction and the resulting performance of the TFTs, the substrate was put into a stretch machine that we designed. When a sample, which is initially 21 mm in length, is stretched up to 31.5 mm, the resulting elastic elongation is 50 percent. We used multiple 21-mm samples and measured the performance of the TFTs in the relaxed state after being repeatedly stretched and relaxed at various elongations from 20 percent to 50 percent. Figure 5 shows the evolution of transfer characteristics as a function of stretching strain. The performance of oxide TFTs remained almost unchanged, and stable even after the sample was repeatedly stretched up to 50 percent and relaxed 10 times. The μ_{FE} is 13.8 ± 1.2 cm^2/V.s, V_{ON} of 0.1 ± 0.2 V, and SS of 0.18 ± 0.05 V/dec. The stable operation indicates that UV/O_3-treated islands are effective in releasing mechanical strains.

We believe this methodology was successful because the oxide TFTs were transferred onto the modified PDMS substrate in the form of islands that were hardened, so that the mechanical stretching of the material occurred mainly in the untreated PDMS regions. The elastic modulus of the stiff, silica-like layer was reported to increase over 10 times compared to the untreated PDMS, while the total thickness is ~5 μm with a gradient depth profile.[17] Since the islands are stiffer than the surrounding PDMS regions, the components on the islands experience very little strain when the sample is macroscopically stretched. Furthermore, the NP oxide TFTs have proven to be more mechanically stable than TFTs that are not located in the neutral bending plane.[16] By combining the modified PDMS substrate and the oxide TFTs located in the neutral bending plane, highly stretchable oxide TFT structures can be achieved.

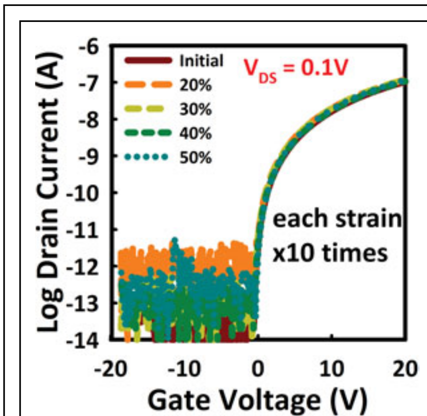

Fig. 5: The stretchability of the oxide TFTs on PDMS substrate is shown above, with the evolution of transfer curves as a function of stretching strain for the oxide TFT. The TFT performance is measured in the relaxed condition after being stretched 10 times for each strain.[18]

Enabling Stretchable, Wearable Displays

We have thus reported the results of a simple integration of neutral-plane oxide TFTs onto a selectively modified PDMS substrate to achieve stretchable properties. The oxide TFTs described in this article show μ_{FE} ~14 cm^2/V.s and change <8 percent during repeated stretching up to 50 percent. The stretchability can be further improved by optimizing the materials and properly designing the structures and transfer methods. The robustness of the stretchable devices can be enhanced by reducing the overall thickness, inserting adhesive layers between TFT membrane and PDMS substrate, or employing an encapsulation layer (*i.e.,* elastic PDMS) on the top. Looking forward, we are now developing an AMOLED on a stretchable substrate (PDMS) using an oxide TFT backplane on a PI substrate. Thermal evaporations of organic semiconductors are used for the OLED-on-TFT array, and then the thin-film encapsulation process is carried out. The AMOLED is cut into small slots and then transferred into the PDMS after being cut.

Combining high mobility, excellent uniformity, and stability with the mechanical robustness of stretchable substrates, oxide TFT technology can provide exciting opportunities in wearable electronics, including stretchable display and skin-like sensors.

References

[1]B. K. Sharma, *et al.*, "Flexible and stretchable oxide electronics," *Adv. Electron. Mater.* **2**(8), 1600105-1-17, 2016.

[2]S.-K. Lee, *et al.*, "Stretchable graphene transistors with printed dielectrics and gate electrodes," *Nano Lett.* **11**, 4642–4646, 2011.

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Developing Liquid-Crystal Functionalized Fabrics for Wearable Sensors

Textiles are the most universal wearable interface. Textile functionality is being rapidly expanded to incorporate a wide range of new technologies. A new concept of combining liquid crystals with fibers effectively incorporates all of the functionality associated with liquid crystals. In this article we report how liquid crystals can be incorporated into fibers and fabrics that respond visually to temperature. Looking to the future, we can envision how these liquid-crystal fabrics can be designed to respond to chemical and biological stimuli, signaling the presence of bacteria and viruses, and opening the potential for wearable medical sensors. In addition to the visual response, the fabrics can provide an electrical output, allowing them to be integrated into more sophisticated sensing systems.

by Junren Wang, Antal Jákli, Yu Guan, Shaohai Fu, and John West

In 1996, researchers at Georgia Tech prototyped the world's first wearable motherboard[1] or "intelligent" garment. This smart garment utilized optical fibers to detect bullet wounds, and special sensors and interconnects to monitor the body's vital signs, with the aim of rescuing soldiers by monitoring their health status in real time. Recently, textile functionality has been expanded to incorporate a wide range of new technologies.[2,3] Some wearable products, like Google Glass,[4] the Apple Watch,[5] and e-Tint eyewear[6] are commercially available. Although "smart," these products are not as flexible as fabrics and work differently from clothes.

Junren Wang, Antal Jákli, and John West are with the Liquid Crystal Institute at Kent State University. Wang and West are also affiliated with the Department of Chemistry and Biochemistry at Kent State and the Institute of Smart Liquid Crystal Technologies at JITRI. Yu Guan and Shaohai Fu are with the Engineering Research Center for Digital Textile Inkjet Printing at Jiangnan University. West can be reached at jlwest@kent.edu.

The vast majority of synthetic fibers for textiles are manufactured using an extrusion process that involves pushing the melt or solution of the synthetic material through a spinneret to form filaments of the polymer or inorganic glass.[7] The resulting fibers are used in a wide variety of applications, ranging from fabrics to complex fiber optic cables that make our communications network possible. Fiber-based devices and systems have outstanding flexibility, wearing comfort, and superior long-term fatigue resistance against large and repeated deformations. They are therefore well-suited for wearable applications.

As with many engineered materials, biology provides motivation and models for optimizing the fabrication and high performance of fibers. For example, spider silk is formed via a spinneret, utilizing fibroin proteins that produce a nematic liquid-crystal structure during the drawing process.[8] The nematic alignment is essential to producing the high strength of the resulting fibers.[9] Mimicking this naturally occurring process, Kevlar fibers[10] were developed. These fibers have a highly ordered molecular structure and are produced using cold-spinning of a liquid-crystalline solution. Recent advancements in nanoscience and technology make it possible to replicate the complexity found in natural fibers and to add functionality not found in nature.

Wearable Sensors

We are particularly interested in forming wearable sensors. Sensors transform one type of signal into another. Different functional materials and structures have the capacity of transforming signals. These include color-changing materials,[11] shape memory materials,[12] and some bioinspired or biomimetic materials,[13,14] just to mention a few. Thermotropic liquid crystals (discovered in 1888[15]) are extremely useful for sensing due to their sensitive response to a variety of external stimuli. This is because they combine the fluidity of isotropic liquids with the anisotropy of crystals. Their large optical response to low voltages has led to their domination of today's flat-panel display industry. The next generation of liquid-crystal devices is expected to continue exploiting this material's sensitivity for signal transduction, but this time as

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wearable thermal,[16] chemical,[17] and biomedical[18–20] sensors.

The color of chiral liquid crystals changes as their temperature varies. The color results from the spiral structure of the elongated molecules and the resulting periodic variation of the refractive index. The period of rotation, or pitch, is temperature-dependent and can be adjusted to coincide with the wavelength of visible light.

Liquid-Crystal Capsules

Thermochromic liquid crystals were first utilized about 50 years ago to sense temperature variations by spraying them directly on human skin.[21] Later studies and patents in the 1970s reported using liquid-crystal thermography for evaluating inflammatory conditions[22] and/or breast tumor detection.[23,24] While technically effective, clinical application of liquid-crystal thermography was not successful. The procedure was often time consuming and messy, since it required either the patient's skin to be painted black and then coated with an oily liquid-crystal film, or a flexible film to be stretched over the skin to display the temperature map.[22] To eliminate the complications and messiness of prior art techniques, we utilized thermochromic liquid-crystal capsules rather than unencapsulated and oily liquid-crystal materials.

The scanning electron microscope (SEM) image in Fig. 1 shows the morphology of commercially available thermochromic LC capsules fabricated by LCR Hallcrest.[25] These spherical capsules are in sizes of several micrometers – several times smaller than the diameter of human hair. For each capsule, a thin and transparent polymer sheath encapsulates the thermochromic liquid crystal inside. These capsules [Fig. 2(a)] can also be embedded into fibers [Fig. 2(b)] by spinning a mixture of capsules and polymer solution.[26] This represents a ruggedized approach, as the incorporated liquid-crystal capsules are locked into the flexible polymer fibers; therefore the fabric can be washed without losing the color response (Fig. 2).

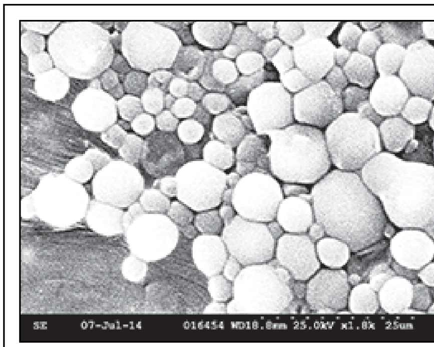

Fig. 1: A scanning electron microscope (SEM) image shows thermochromic liquid crystals in capsule form.

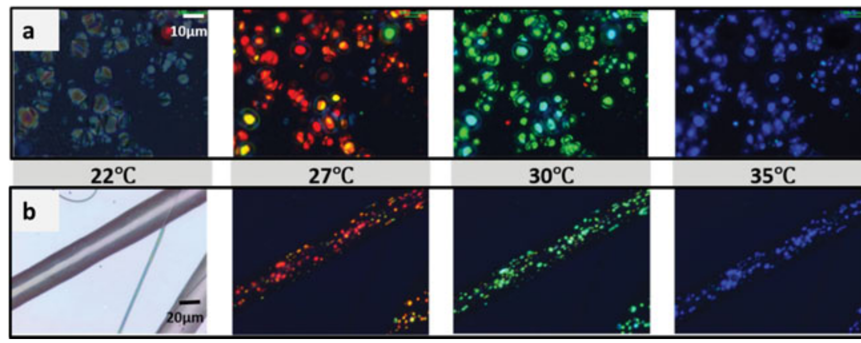

Fig. 2: (a) These reflected microscopic images of thermochromic liquid-crystal capsules result from different temperatures. (b) Fibers containing these capsules respond to varying temperatures by reflecting different colors.[26]

Liquid-Crystal Capsule Coating

With the protection of the sheath, these thermochromic capsules can be directly sprayed and/or printed onto the surface of an object to form a film. The impact of this reflected color is maximized when the chiral-nematic material is presented against a black background. For example, the capsules can be sprayed onto a black bandage to become a diagnostic medical tool to detect the arteries and veins in the wrist (Fig. 3).

In order to achieve the required sensitivity, the color has to change over a narrow (1–2°C) temperature range. Variations in average skin temperature among individuals and even in different circumstances in a single individual (such as mood) change the skin temperature and therefore can easily move out of the color response range of the selected chiral nematic mixture. Therefore, if the fabric only utilizes one chiral liquid-crystal formulation, it has the drawback of a narrow operating temperature range.

To allow the thermochromic fabric to have a high thermal sensitivity over a broad temperature range, we printed different patterns of multiple thermochromic capsule formulations whose visible thermochromic response occurs at different, adjacent, and complementary temperature ranges on a single fabric.[27]

Through simple paper stencils, these different mixtures are sprayed or printed into different patterns on the thermochromic fabric. The patterns provide another visual temperature reference that allows for high sensitivity and broad range. Figure 4 shows the thermal pattern of a human hand imaged on the fabric compared to a thermal camera image of the same hand.[26] The fabric clearly shows how the printing of different chiral-nematic formulations in different patterns (a solid line, rectangles, and rhomboids) results in a sensitive thermochromic effect that operates over a broad temperature range. The same ensemble of thermochromic capsules can also be sprayed or printed on a tie

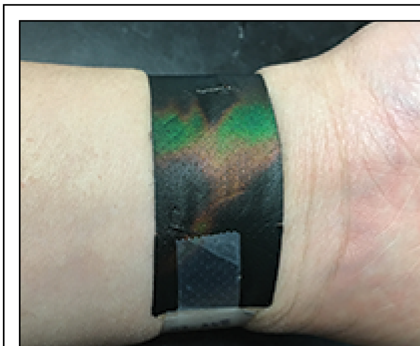

Fig. 3: Thermochromic capsules sprayed on a black bandage sense the arteries and veins located in the wrist area.

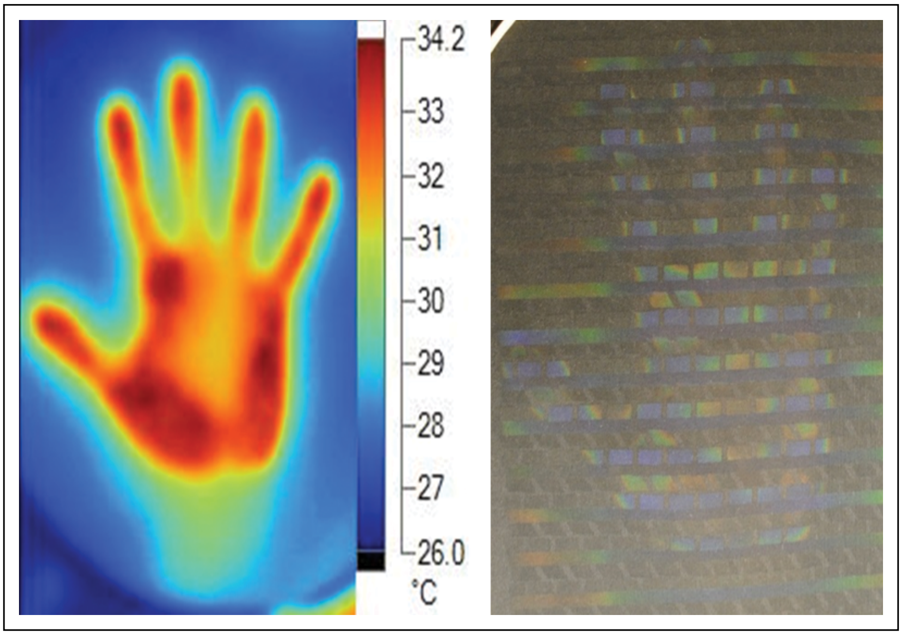

Fig. 4: Compare the thermal pattern of a human hand imaged on a thermochromic fabric (right) to a thermal camera image of the same hand (left).[26]

to exhibit their fashion function. In this example, the color patterns of the tie change with changes in temperature, creating a chameleon effect (Fig. 5).[26]

Liquid Crystals/Polymer Cores/Sheath Fibers

Additionally, fluid liquid crystals can be embedded in fibers as a continuous liquid-crystal core surrounded by a polymer sheath. With the core/sheath structure, the polymer sheath protects the liquid crystals from harsh environments. The fiber structure and large surface-area-to-volume ratios place the liquid crystals in intimate contact with the external environment, increasing their sensitivity and response to changes in temperature[28,29] and chemical vapors,[30] *etc*. Direct incorporation of liquid crystal within polymer fibers was studied first by Lagerwall, *et al.*,[31] by using coaxial electrospinning, and then by West, *et al.*,[29,32] by using single spinneret spinning and relying on spontaneous phase separation during the spinning process. By varying the working parameters during the spinning process,[33,34] the morphologies of resulting fibers can be tuned between a beads-on-a-string structure and a uniform tubing structure (Fig. 6).

By spinning a solution containing a polymer and a temperature-sensitive chiral-nematic liquid crystal, non-woven liquid-crystal fiber mats can be obtained. The resulting fibers with different morphology show thermochromic response to changes in temperature as well (Fig. 7).

Instead of printing different thermochromic capsules in patterns on a black fabric, as shown in Fig. 4, we can fabricate complex fabrics by utilizing multi-spinning [Fig. 8(a)]. This produces fiber mats consisting of multiple fibers containing different liquid-crystal compositions.[26] The multi-jet electrospinning has been demonstrated as a 3D fabric printer (Electroloom[35]) and used to create a fabric for wearing. As shown in Fig. 8(b), using the rotating drum as a collector, the resulting fibers can be aligned and uniformly distributed. Importantly, the resulting hybrid fiber mats also possess enhanced capacity to respond to a variety of stimuli, since they contain different liquid crystals.

Applications

We are at the infancy of the development of responsive liquid-crystal fibers. We anticipate many applications of responsive liquid-crystal

Fig. 5: In a fashion application, a tie is coated with thermochromic liquid-crystal capsules.[26]

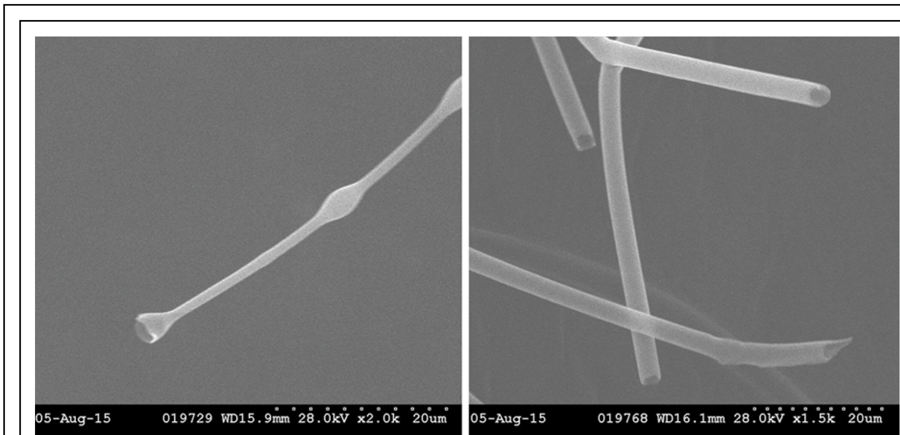

Fig. 6: These are examples of SEM images of liquid crystal/polymer fibers with different morphology – beads-on-a-string (left) and uniform core/sheath (right) fibers.

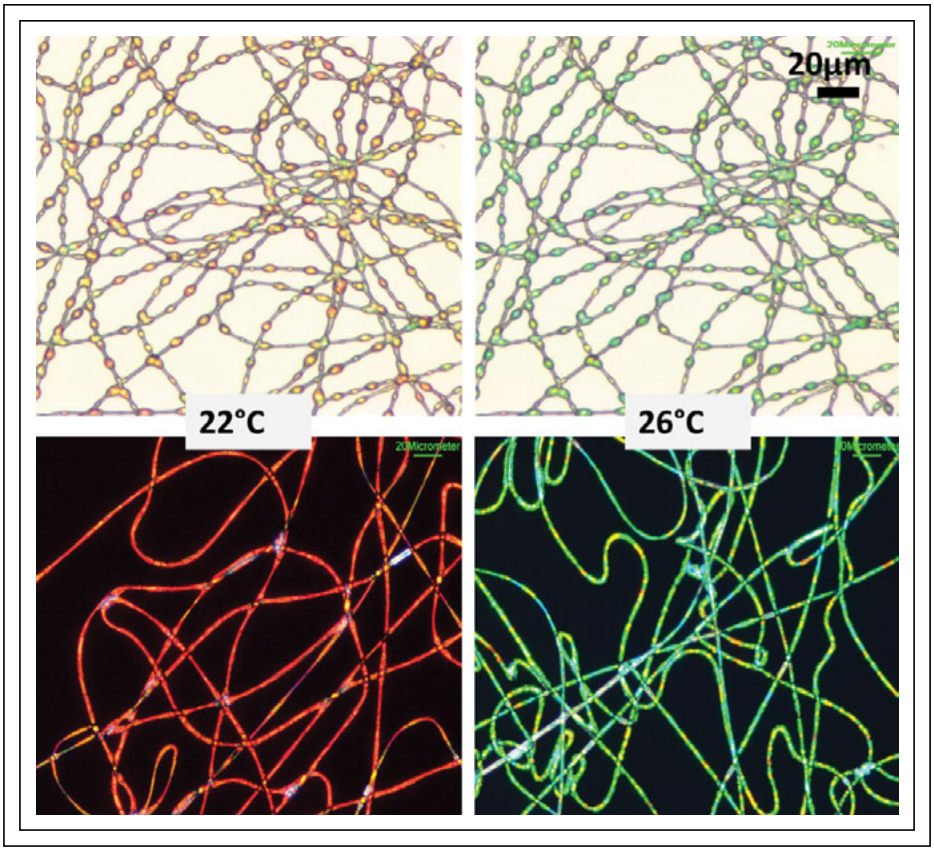

Fig. 7: Microscope images show how liquid-crystal fibers respond to temperature by reflecting different colors.

fabrics and garments. The simple thermochromic fabric or garment may be worn on specific body parts of a patient. This may provide the first "killer" application as an effective medical diagnostic sensor that will move the technology from the laboratory to the marketplace. For example, a sock made from these fabrics could provide an early indication of foot ulcers in diabetic patients,[36] a leading cause of complications and death from this increasingly common disease. Thermochromic fabrics could be fashioned into leggings worn by bedridden hospital patients, providing nurses and doctors with a quick, early warning of the development of a life-threatening thrombosis. As noted above, the thermochromic fabrics could be included in bandages to evaluate conditions of a developing infection and changes in blood circulation. As with the evolution of the LCD, these early, simple applications will undoubtedly be followed by increasingly sophisticated chemical and biological sensors that provide a range of visual, optical, and electrical outputs.

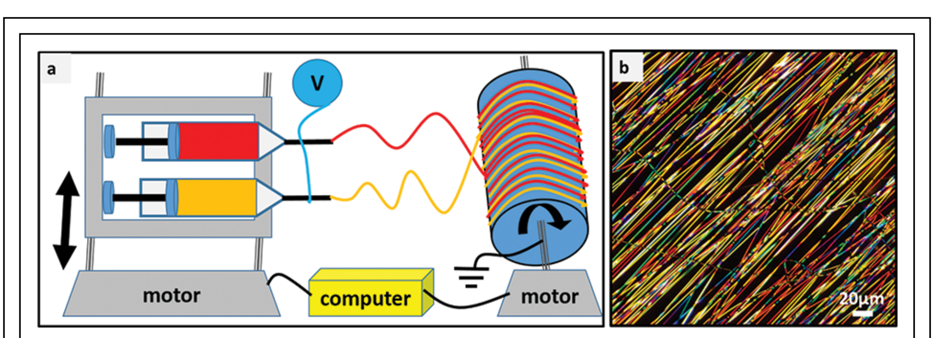

Fig. 8: In the multi-electrospinning set-up in (a), the spinnerets and rotating drum are moved or driven by a separate motor, which can be controlled by a computer. In (b) is shown a polarized microscopic image of aligned liquid-crystal/polymer fibers collected with the rotating drum.

With Further R&D, the Potential Is Huge

To summarize, this article points to potential early applications of responsive liquid-crystal textiles for use as medical sensors. It predicts that these early applications will lead to more complex wearable sensors. We discussed and demonstrated that the next generation of liquid-crystal devices will be wearable and will exploit their sensitivity to thermal, chemical, and biological stimuli. This evolution requires a rethinking of how liquid-crystal devices are designed and fabricated. Incorporating liquid crystals into fibers, fabrics, and garments places the materials in contact with the external environment. Specifically, we reported the fabrication and performance of thermochromic fabrics that incorporate liquid crystals, either as microcapsules bonded to the fiber surface, or as coaxial fibers consisting of a liquid-crystal core surrounded by a polymer sheath. Such fibers and their assembly are as flexible and breathable as conventional fabrics.

Much research and development remain for our vision to become a reality. For example, the specific binding agents must be incorporated in the polymer sheath if we are to produce fibers that respond to specific chemicals or biological agents in the environment. We must also increase the durability of the fibers by crosslinking the polymer sheath and by utilizing thermally wide and chemically stable liquid-crystal formulations.

Acknowledgments

The authors acknowledge the support from Kent State University and Jiangsu Industrial Technology Research Institute (China), and acknowledge the scanning electron microscopy (SEM) characterization facility at Liquid Crystal Institute of Kent State University.

References

[1]www.smartshirt.gatech.edu

[2]B. J. Agarwal and S. Agarwal, "Integrated Performance Textiles Designed for Biomedical Applications," *IPCBEE* **11**, 114–119, 2011.

[3]A. Afif, *et al*., "An overview of smart technologies for clothing design and engineering," *Int. J. Cloth. Sci. Technol.* **18**, 108–128, 2006.

[4]www.google.com/glass/start

[5]www.apple.com/watch

[6]http://alphamicron.com

[7]*Advanced Fiber Spinning Technology,* Woodhead Publishing, 1994.

[8]F. Vollrath and D. P. Knight, "Liquid crystalline spinning of spider silk," *Nature* **410**, 541–548, 2001.

[9]D. P. Knight and F. Vollrath, "Spinning an elastic ribbon of spider silk," *Phil. Trans. R. Soc. Lond. B* **357**, 219–227, 2002.

[10]www.dupont.com/products-and-services/fabrics-fibers-nonwovens/fibers/brands/kevlar/products/dupont-kevlar-fiber.html

[11]M. Ferrara and M. Bengsu, *Materials that Change Color: Smart Materials, Intelligent Design*, Springer Science & Business Media, 2013.

[12]W. M. Huang, *et al*., "Shape memory materials," *Mater*. *Today* **13**, 54–61 (2010).

[13]N. Zhao, *et al.*, "Bioinspired materials: From low to high dimensional structure," *Adv. Mater*. **26**, 6994–7017, 2014.

[14]M. Ebara, *et al., Smart Biomaterials,* Springer Japan, 2014

[15]F. Reinitzer, "Beiträge zur Kenntniss des Cholesterins," *Monatshefte für Chemie und verwandte Teile anderer Wissenschaften* **9**, 421–441, 1888.

[16]L. Gao, *et al.*, "Epidermal photonic devices for quantitative imaging of temperature and thermal transport characteristics of the skin," *Nat. Commun*. **5**, 4938, 2014.

[17]C. G. Reyes, A. Sharma, and J. P. F. Lagerwall, "Non-electronic gas sensors from electrospun mats of liquid crystal core fibres for detecting volatile organic compounds at room temperature," *Liq. Cryst*. **43**, 1986–2001, 2016.

[18]J. M. Brake, M. K. Daschner, Y. Luk, and N. L. Abbott, "Biomolecular Interactions at Phospholipid-Decorated Surfaces of Liquid Crystal," *Science* **302**, 2094–2097, 2003.

[19]S. Sivakumar, K. L. Wark, J. K. Gupta, N. L. Abbott, and F. Caruso, "Liquid crystal emulsions as the basis of biological sensors for the optical detection of bacteria and viruses," *Adv. Funct. Mater*. **19**, 2260–2265, 2009.

[20]S. J. Woltman, G. D. Jay, and G. P. Crawford, "Liquid-crystal materials find a new order in biomedical applications," *Nat. Mater*. **6**, 929–938, 2007.

[21]J. Fergason, *Life Magazine*, Jan. 18, 1968.

[22]M. Shlens, M. R. Stoltz, and A. Benjamin, "Orthopedic applications of liquid crystal thermography," *West. J. Med*. **122**, 367–70, 1975.

[23]E. Gitsch, "The value of liquid crystal thermography in the detection of breast cancer by the gynaecologist (author's transl)," *Wien. Klin. Wochenschr*. **88**, 737–740, 1976.

[24]R. Pochaczevsky and P. H. Meyers, "Vacuum contoured, liquid crystal, dynamic breast thermoangiography as an aid to mammography in the detection of breast cancer," *Clin. Radiol*. **30**, 405–411, 1979.

[25]www.hallcrest.com

[26]J. Wang, *et al*., "Smart Fabrics Functionalized by Liquid Crystals," *SID Symp. Digest of Tech. Papers* **48**, 2017.

[27]J. L. West, *et al*., "Thermochromic fabrics utilizing cholesteric liquid crystal material," US patent 20150173679 A1, 2015.

[28]E. Enz and J. Lagerwall, "Electrospun microfibres with temperature sensitive iridescence from encapsulated cholesteric liquid crystal," *J. Mater. Chem*. **20**, 6866–6872, 2010.

[29]J. Wang, A. .Jákli, and J. L. West, "Airbrush Formation of Liquid Crystal/Polymer Fibers," *ChemPhysChem* **16**, 1839–1841, 2015.

[30]C. G. Reyes, A. Sharma, and J. P. F. Lagerwall, "Non-electronic gas sensors from electrospun mats of liquid crystal core fibres for detecting volatile organic compounds at room temperature," *Liq. Cryst*. **43**, 2016.

[31]J. P. F. Lagerwall, J. T. McCann, E. Formo, G. Scalia, and Y. Xia, "Coaxial electrospinning of microfibres with liquid crystal in the core," *Chem. Commun. (Camb)*. 5420–5422, 2008.

[32]E. A. Buyuktanir, M. W. Frey, and J. L. West, "Self-assembled, optically responsive nematic liquid crystal/polymer core-shell fibers: Formation and characterization," *Polymer (Guildf)* **51**, 4823–4830, 2010.

[33]J. Wang, A. Jákli, and J. L. West, "Morphology Tuning of Electrospun Liquid Crystal/Polymer Fibers," *ChemPhysChem* **17**, 3080–3085, 2016.

[34]J. L. West, J. R. Wang, and A. Jákli, "Airbrushed Liquid Crystal/Polymer Fibers for Responsive Textiles," *Adv. Sci. Technol*. **100**, 43–49, 2016.

[35]www.kickstarter.com/projects/electroloom/electroloom-the-worlds-first-3d-fabric-printer.

[36]N. Singh, D. G. Armstrong, and B. A. Lipsky, "Preventing foot ulcers in patients with diabetes," *J. Am. Med. Assoc*. **293**, 217–228, 2005. ■

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New Polymer Materials Enable a Variety of Flexible Substrates

The Pylux family of polysulfide thermosetting polymers (PSTs) has been developed to enhance manufacturing options for a wide range of flexible displays and electronics.

by Tolis Voutsas, Radu Reit, Adrian Avendano, David Arreaga, and John Dupree

THE flat-panel display industry has made a remarkable journey since its beginnings in the early 1980s. Continuous improvements in materials, processes, and device technologies have rapidly transformed clunky, power-hungry, and inelegant early displays to thin, high-resolution, brilliant, and aesthetically pleasing panels that have completely transformed the way we communicate and interact.[1,2] All this has been accomplished with the same fundamental form factor, consisting of an essentially rigid display surface. Overcoming this constraint has been the focus of intense R&D work, almost since the very first days of flat panels, to enable new and innovative flexible form factors.[3,4] According to the 2016 IHS Market Tracker, the market for flexible displays is expected to grow to $26 billion by 2023.[5]

The most stubborn technical challenge of making a flexible display has been finding a suitable substrate material. Beyond the obvious requirement of being flexible, the substrate must satisfy a combination of several, often conflicting, physical properties while at the same time allowing ease of manufacturing and low cost to display fabricators. Over the years, different types of flexible substrates have been developed and evaluated, including inorganic materials (thin metal foil,[6] thin glass[7,8]) and organic materials (polyimide or PI[9]). In terms of organic materials, polyimide has become, by default, the current industry standard, primarily due to its operating temperature range and the sheer amount of research that has been done to fit it into pilot manufacturing.

The comparison in Table 1 of various flexible substrates that have been adapted to

Tolis Voutsas, Radu Reit, Adrian Avendano, David Arreaga, *and* ***John Dupree*** *are with Ares Materials, Inc. Voutsas can be reached at tolis@aresmaterials.com.*

Table 1: Comparison of substrate materials for flexible displays

Property	Thin Glass	Thin Metal Foil	Polyimid
Operating Temperature(1)	Good	Excellent	Good
Transparency	Excellent	(Not transparent)	Not Good
Surface Roughness	Excellent	Not Good	Not Good
Colorless	Excellent	(Not transparent)	Not Good
Weight(2)	Not Good	Not Good	Excellent
Ruggedness(3)	Not Good	Excellent	Excellent
Small ROC(4)	Not Good	Not Good	Excellent
Release from Carrier(5)	Costly	Costly	Costly
Product Scalability(6)	Unclear	Unclear	Limited
Cost	Expensive	Unclear	Expensive

(1) The maximum temperature the substrate can be exposed without degradation.
(2) For the same thickness.
(3) Refers to ability to withstand impact without damage.
(4) ROC=Radius of Curvature (typically need <0.5mm for various flexible embodiments).
(5) Laser-Lift-Off (LLO) process is used to release flex substrate from rigid carrier, which is a very expensive and defect-prone process.
(6) Refers to the maximum size display that can be made on the flex substrate. Currently, on PI the display size is limited to ~6" diagonal mostly due to defect density during release.

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flexible display manufacturing indicates that there is no one ideal substrate option, even though substrate materials themselves represent a lucrative \$1 to \$2 billion market. Substrates are still dominated by outdated materials, some of which date back to the 1930s and 1950s. Part of the problem is that incumbent providers are large, entrenched, and not incentivized to innovate, since innovation would cannibalize their existing market. They are therefore committed to incremental changes within existing technology platforms. The result is a gap between what existing material systems can deliver and what the display industry needs to create new product categories.

To help close this gap, the authors' company developed the Pylux family of polysulfide thermosetting polymers (PSTs). The PST family is the culmination of more than 10 years of research at the University of Texas at Dallas, initially around novel materials for neural interfaces. These devices, which intimately contact the central and peripheral nervous system, undergo many of the same stringent thermal and chemical processes as displays during their photolithographic definition (*e.g.,* high-temperature PECVD for SiN_x encapsulation layers, wet-etch protocols, lift-off processing, *etc.*). After successfully building devices for neural interface applications, the team discovered that those materials had applications beyond biomedical implants, not the least of which was offering substrate options to the global display industry. The development and commercialization of PSTs for the flexible electronics space provided the impetus around which the company, Ares Materials, was founded in 2014.

PST Characteristics

PSTs have been formulated precisely for the needs of the flexible electronics industry. The polymer resin can be die-coated or spin-casted at the target thickness and then cured to form a solid film. Its formulation process does not use solvents, which provides for significant cost savings for display manufacturers in terms of process time (less curing time), and raw materials costs. Lack of solvents also translates to a safer and greener process. The resulting solid film is colorless, with high optical transmission (>90% in 450-nm to 800-nm range) and an extremely smooth surface (<0.5-nm surface roughness). This low surface roughness is another key advantage, as it eliminates the need for a surface planarization layer prior to microfabrication of electronic devices and circuits. Figure 1 compares the fabrication process for PST and PI film.

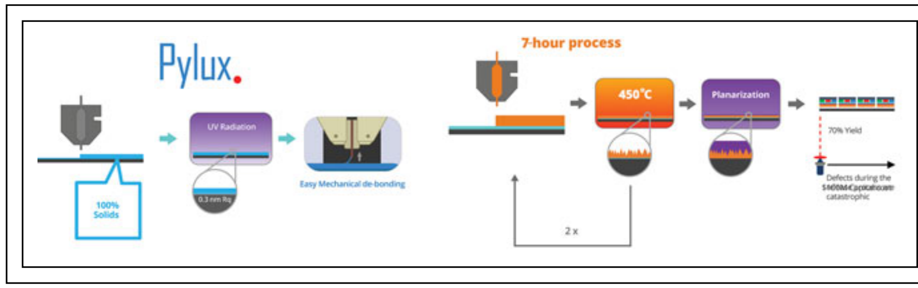

Fig. 1: The preparation process for Pylux is shown at left, and that for polyimide substrates is shown at right.

PST films not only have much lower cure stress than polyimide, but the development of special release layers allows for easy detachment of the film from the underlying carrier using only a mechanical process. This has two distinct advantages over other methods: It eliminates the need for laser-liftoff (LLO), which is a capital-intensive and relatively slow process, and it significantly improves release yield by reducing the occurrence of potentially catastrophic defects during the release process. As a result, both manufacturing cost and manufactured product size can be significantly improved.

Polyimide substrates are solution cast from precursor poly(amic acid) solutions, wherein solvated poly(amic acid) is coated onto the mother glass carrier and baked to remove the high solvent fraction (> 80%). Next, further baking of the dried poly(amic acid) is carefully performed under inert atmospheres to imidize the film and set the final polyimide film. In contrast, PST resin is dispensed onto the mother glass carrier using similar coating techniques (*e.g.,* slot-die coating), where the zero-solvent system can convert the wet film completely to a dry film. Additionally, the material can be converted to the final film in an ambient environment via ultraviolet curing or thermal curing at temperatures below 250°C. PST films show excellent thermal stability up to temperatures of 300°C, with no evolved sulfur species that may interact with subsequent thin-film layers. Processes for both Pylux and PI are diagrammed in Fig. 1.

Table 2 summarizes various key properties for PST films. Since most flexible substrates in use today are made from clear polyimide (CPI), CPI-equivalent parameters have been included when available.[10] It is important to note that PST's glass transition (Tg) and coefficient of thermal expansion (CTE) are quite different from the equivalent parameters for typical display-grade polymers. While PST films have a higher Tg and CTE compared to

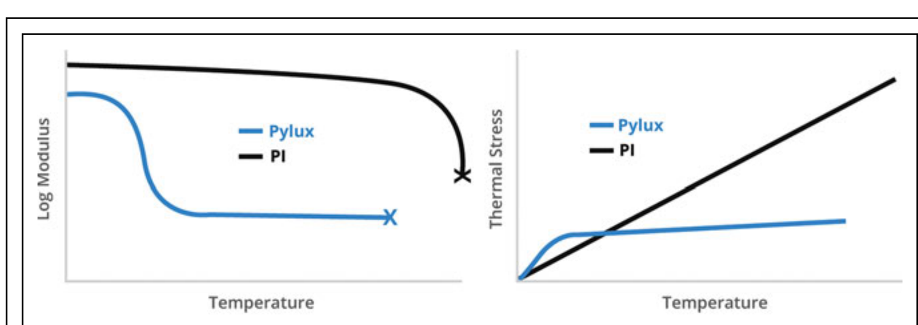

Fig. 2: (a) A log-linear example plots Young's modulus vs. temperature for Pylux and general polyimides, with thermal degradation temperatures represented by Xs. (b) Total thermal stress in thin films deposited atop each substrate is shown as a function of temperature.

Table 2: Pylux and clear PI are compared in terms of key properties[1]

Category	Property	Pylux™	Clear PI
Mechanical	Cure Temp (°C)	23	>300
	Surface Roughness (nm)	<0.5	<10
	Tensile Modulus (GPa)	2	3 - 6
	Tensile Strength (MPa)	50	130 - 250
	Elongation (%)	10	
Thermal	Tg (°C)	55	>330
	Tmax (°C)	300	450 [2]
	CTE (50-250°C) (ppm/°C)	150	<15
	1% Weight Loss (°C)	275	
	300°C/3 hr Weight Loss (%)	4	
Optical	Total Transmittance @ 400-800nm (%)	>90	>88 (at 550nm)
	Haze (%)	0.46	<1
	Refractive Index	1.544	1.7 [2]
	Birefringence @ 633nm (nm/cm)	42 nm / cm	8×10^{6} [3]
	b* (measure of yellow index)	3.23	5-12 [4]
Chemical	Resistance to common acids and solvents	Excellent resistance (10-30 min at RT)	Resistance reported but may need extra coatings
Manufacturing	Special Planarization Needed	No	Yes
	Method to Release from Rigid Carrier	Mechanical Lift-off	LLO
	Refractive Index	X1	X3

(1) Kolon's CPI material: http://www.fuentek.com/technologies/CPI/#techdet

(2) http://www.brewerscience.com/uploads/publications/2003/sm_spie_osd_paper.pdf

(3) Data for PI (not CPI)

(4) See: C.P. Yang and Y.Y Su, Polymer, vol. 46, pp. 5797-5807, 2005.

currently used substrates for flexible electronics, these parameters actually comprise the principle used to allow PST to introduce lower stresses related to thermal-cycling thin films deposited atop it. The primary mechanism behind this stress reduction is related to both the lowered Young's modulus (E) of PST throughout the entire deposition temperature range and to the Tg that further reduces the modulus another two orders of magnitude at the low temperature of 55°C.

Often-cited examples for understanding thin-film stresses that accumulate in multilayer structures include the original Stoney formula for bi-material strips, as well as the countless modifications and expansions of this initial formula.[11–17] In these calculations, the total stress observed by a thin-film (σf) for two substrates of equal dimensions reduces to a direct proportionality between the thin-film stress and the Young's modulus of the substrate ($\sigma f \propto Es$). As shown in Fig. 2(a), this is reflected by the low Tg and lowered glassy E of PST. Effectively, this translates to a lowered buildup of thermal stress in the thin films deposited atop the substrate material [Fig. 2(b)], where despite the higher thermal stress-ramp rate close to Tg for PST, the transition from glass to rubber allows for a more attenuated thermal-stress buildup at temperatures subsequent to the Tg. While this is only a brief overview of the mechanics under which the PST operates to accommodate mechanical mismatch with a variety of thin-film materials, the explanation serves as a good starting point for exploring the use of alternative substrates for flexible electronics.

Figure 3 summarizes the operating temperature range for PST and several other types of polymer substrates. Despite its lower maximum temperature (*e.g.*, as compared to PI/CPI), PST is the only material that shows no observable mechanical mismatch over its full operating temperature range. The lower maximum temperature that PST can be exposed to (~300°C) *vs.* that of PI/CPI (~400–450°C) means that it is not suitable for current LTPS-TFT processes. However, current industry trends point toward the eventual adoption of oxide-TFT processes to reduce array manufacturing costs. Since oxide-TFT fabrication can be accomplished at a temperature range that is compatible with PST,[18–21] PST will not only be a very desirable substrate option for oxide-based flexible displays, but its very availability should spur market evolution to oxide TFTs. Moreover, the combination of superior dimensional stability, low stress, and excellent adhesion also provide a compelling case for the penetration of PST into the emerging area of OTFT (organic TFT)-based flexible arrays.[22] The data in Table 2 also highlight the excellent optical characteristics of PST beyond transparency, such as low haze, very low birefringence, and low yellow index. These reveal another host of front-plane applications for PST that are difficult (or impossible) to access by competing material solutions (*e.g.,* CPI) due to inferior characteristics and/or high cost. Figure 3 shows critical temperature details for various polymer substrate materials.

Examples of PST Applications

Figure 4 summarizes some of the possible applications of PST material in LCD and OLED stacks. Based on its combined optical, mechanical, and thermal properties, PST will be able to provide material solutions for the TFT substrate, color filter substrate, touch sensor substrate, cover lens, and OCA. Currently, Ares is working with various partners to test and optimize the PST material for these applications. We have already fabricated IGZO-TFT on PST and compared its performance to that of control devices on silicon substrates (Fig. 5). The thin-film transistors were fabricated on PST at a maximum processing temperature of 250°C. Mobilities of IGZO transistors (W = 100 um; L = 40 um) on PST substrates were an average of 9.1 cm^2/Vs, compared to 9.5 cm^2/Vs for those directly on Si wafers. Similar on-voltages (–0.2 V *vs*. –0.6 V) and subthreshold swings (280 mV/dec *vs*. 293 mV/dec) were also observed when comparing transistor sets on PST substrates *vs*. those on silicon. The close similarity between the performance characteristics of devices fabricated on PST and those of IGZO-TFTs fabricated on Si carrier wafers validates the compatibility of PST with standard IGZO fabrication facilities and process flow. Using our proprietary mechanical release method and release layer, we were able to ensure that the IGZO-TFT characteristics remained stable even after the release of the PST substrate from the rigid carrier.

Although PST was originally formulated for sheet-to-sheet processing, Ares has also been developing roll-to-roll capabilities. Recent work done in collaboration with a third party provides evidence that PST is capable of rapid photo-curing (<10 s) and can be implemented in a web configuration. We are also engineering the basic polymer material to exhibit an increased Tg, which eliminates the need for support liners during web processing. This opens up further applications in the broader space of flexible and printed electronics.

PST Materials Are Poised for a Variety of New Applications

The display industry requires new flexible substrate materials with superior optical, mechanical, chemical, and thermal properties that can provide solutions for various display layers, including the TFT substrate, color filter substrate, touch sensor substrate, cover lens, and OCA. Our PST materials have been formulated with these properties, with expected commercial pricing of net realized material that falls below the current range for high-performance PIs. The PST can be die-coated or spin-casted at the target thickness and then UV-cured to form a solid film. We have already developed a mature sheet-to-sheet process for this material and are in

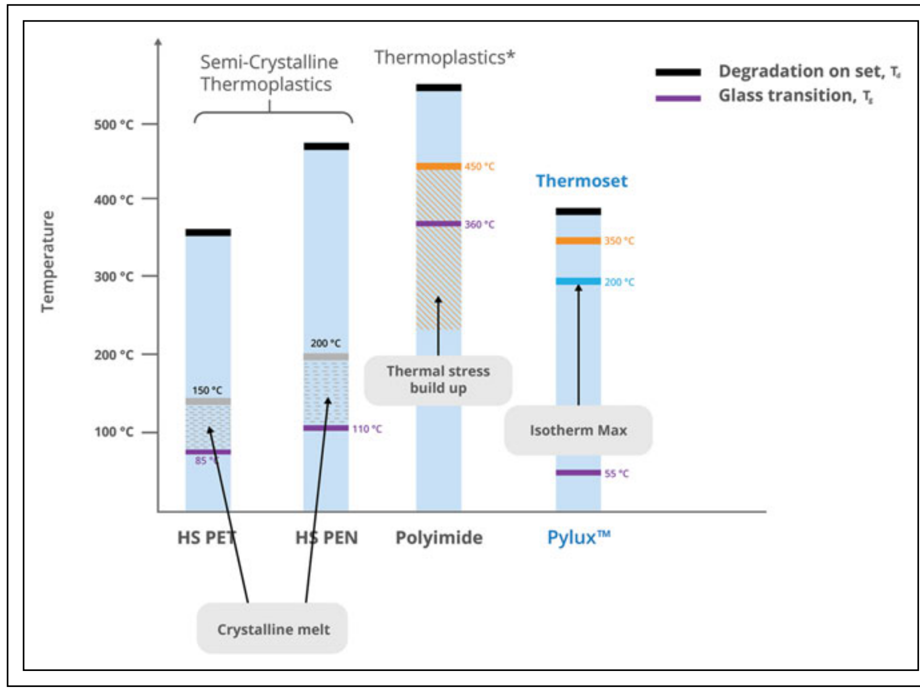

Fig. 3: *Critical temperatures for various polymer substrate materials are compared.*

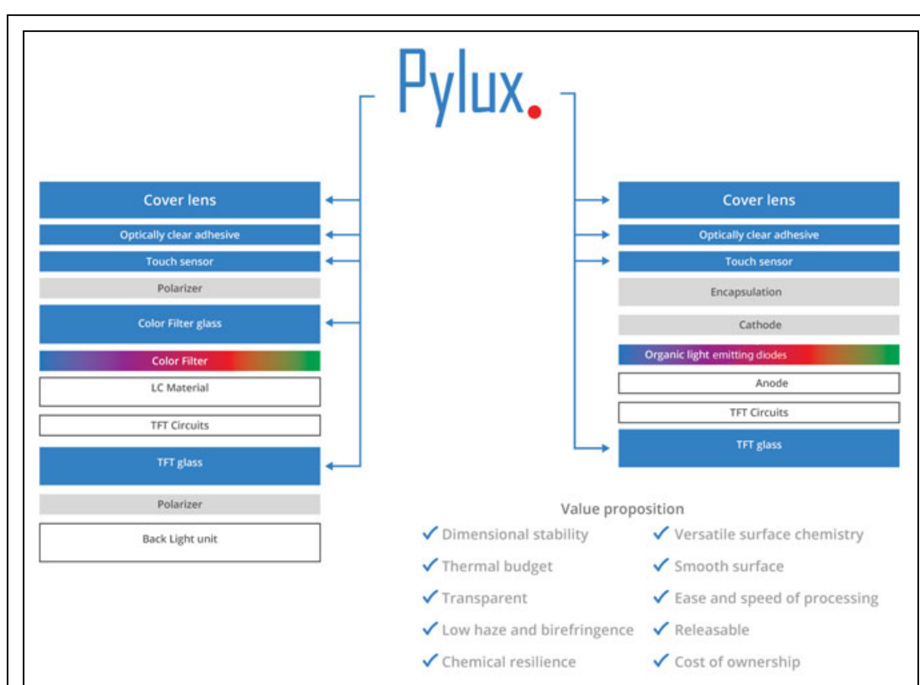

Fig. 4: *Potential PST applications for both AMLCD and AMOLED display stacks are indicated with arrows.*

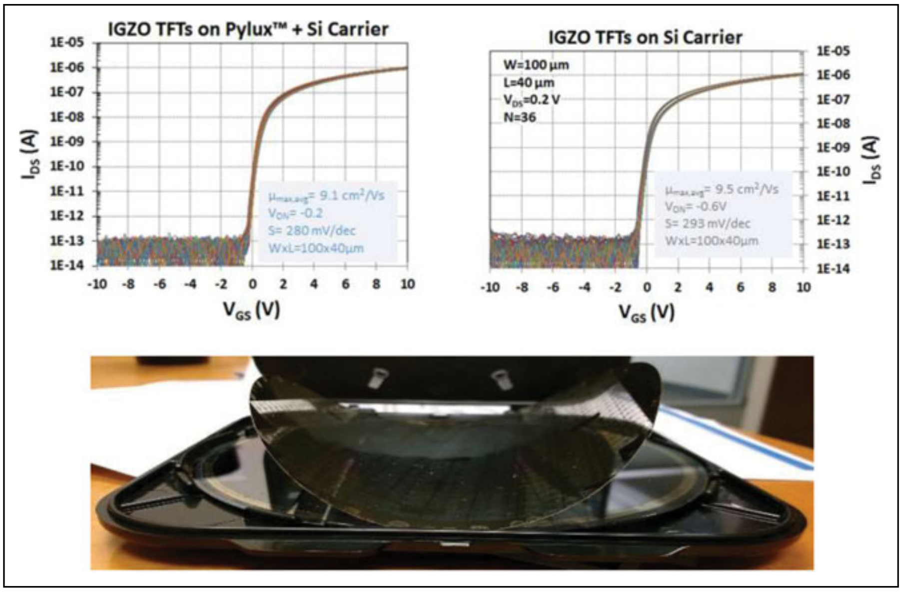

Fig. 5: *At top left are I-V curves for IGZO-TFTs on PST formed on a rigid Si carrier. At top right are I-V curves for IGZO-TFTs on a rigid Si carrier. At bottom is a 100-um PST with IGZO-TFTs after release from a rigid Si carrier.*

on-going development for a qualified roll-to-roll process.

The company is currently working with over a dozen partners around the world to test and optimize our material for the display and non-display applications noted above. We are completing larger display testing (Gen 2 or larger), and have also successfully achieved our first 10x scale increase in the polymer production process, with additional production scale leaps anticipated for later this year. Commercial production is scheduled to commence by the end of 2017.

Note

Pylux refers to the PST family of polymer materials and is a registered trademark of Ares Materials, Inc.

References

[1]M. Kubo, *et al.*, "Flexible High-Resolution Full-Color Top-Emitting Active-Matrix Organic Light Emitting Diode Display," *JSID* **21**, 422–432, 2013.

[2]Y. Yamamoto and A.T. Voutsas, "Technology Trend of AMLCDs for Mobile Application," *Electrochem. Soc. Transactions* **3**, 11–22, 2006.

[3]A. Chida, *et al.*, "Flexible High-Resolution Full-Color Top-Emitting Active-Matrix Organic Light Emitting Diode Display," *JSID* **21**, 422–432, 2013.

[4]R. Komatsu, *et al.*, "Repeatedly Foldable AMOLED Display," *JSID* **23**, 41–49, 2015.

[5]IHS Flexible Display Market Tracker – H2, 2016.

[6]T.-K. Chuang, *et al.*, "Polysilicon TFT Technology on Flexible Metal-Foil for AMPLED Displays," *JSID* **15**, 455–461, 2007.

[7]www.corning.com/worldwide/en/innovation/corning-emerging-innovations/corning-willow-glass.html

[8]www.agc.com/english/products/products_07.html

[9]S. Nakano, *et al.*, "Highly Reliable a-IGZO TFT on a Plastic Substrate for Flexible AMOLED Displays," *JSID* **20**, 493–498, 2012.

[10]www.fuentek.com/technologies/CPI/#techdet

[11]G. G. Stoney, "The Tension of Metallic Films Deposited by Electrolysis," *Math. Phys. Character* **82** (553) 172–175, 1909.

[12]S. Timoshenko, "Analysis of Bi-Metal Thermostats," *J. Opt. Soc. Am.* **11**(3), 233, 1925.

[13]Y. Inoue and Y. Kobatake, "Mechanics of adhesive joints – Part III. Evaluation of residual stresses," *Appl. Sci. Res. Sect. A* **7**(4), 314–324, 1958.

[14]R. Glang, R. A. Holmwood, and R. L. Rosenfeld, "Determination of Stress in Films on Single Crystalline Silicon Substrates," *Rev. Sci. Instrum*. **36**(1), 7–10, 1965.

[15]C. Atkinson and R. V. Craster, "Theoretical aspects of fracture mechanics," *Prog. Aerosp. Sci*. **31**(1), 1–83, 1995.

[16]K. Röll, "Analysis of stress and strain distribution in thin films and substrates," *J. Appl. Phys.* **47**(7), 3224–3229, 1976.

[17]M. Yanaka, Y. Tsukahara, N. Nakaso, and N. Takeda, "Cracking phenomena of brittle films in nanostructure composites analysed by a modified shear lag model with residual strain," *J. Mater. Sci.* **33**(8), 2111–2119, 1998.

[18]J. Lee, *et al.*, "World's Largest (15-inch) XGA AMLCD Panel Using IGZO Oxide TFT," *SID Symp. Digest of Tech. Papers*, 2008.

[19]K. Miura, *et al.*, "Low-Temperature-Processed IGZO TFTs for Flexible AMOLED with Integrated Gate Driver Circuits," *SID Symp. Digest of Tech. Papers*, 2011.

[20]D. Geng, H. M. Kim, M. Mativenga, Y. F. Chen, and J. Jang, "High Resolution Flexible AMOLED with Integrated Gate-Driver using Bulk-Accumulation a-IGZO TFTs," *SID Symp. Digest of Tech. Papers*, 2015.

[21]H. J. Kim, "Various Low-Temperature Activation Methods for IGZO TFTs in Flexible Displays," *SID Symp. Digest of Tech. Papers*, 2016.

[22]C. W. M. Harrison, *et al.*, "Flexible AMOLED Display Driven by Organic TFTs on a Plastic Substrate," *SID Symp. Digest of Tech. Papers*, 2014. ■

Journal of the
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Invitation to submit review papers

The Journal is presently soliciting review papers on any display-related topic. If you have a great idea for a review paper, please contact the editor at **editor@sid.org**.

Selected authors will be invited and the page charges will be waived.

Herbert DeSmet
Editor-in-Chief

Announcements

Impact Factor increase

In June, the 2016 Journal Citation Reports (Clarivate Analytics, 2017) were published. JSID's Journal Impact Factor has gone **up by 42%** and is now at 0.877. Our aim is to continue this trend in the coming years.

JSID Awards

The **JSID Best Paper Award 2016** goes to: **Human visual perception-based localized backlight scaling method for high dynamic range LCDs** | Jae Sung Park et al. | DOI 10.1002/jsid.458

Jae Sung Park

Ruidong Zhu

The **JSID Outstanding Student Paper Award 2016,** *generously sponsored by LG Display*, goes to: **High-ambient-contrast augmented reality with a tunable transmittance liquid crystal film and a functional reflective polarizer** | Ruidong Zhu et al. | DOI 10.1002/jsid.427

Editorial Board updates

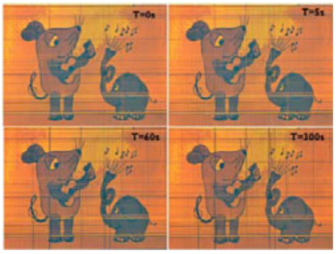
Frank Rochow and Han-Ping Shieh have retired from the Board. We are extremely thankful for their years of excellent service. Four new Associate Editors have recently joined the board: Pengda Hong, Chuan Liu, Dirk Hertel and Abhishek Srivastava.

Expanded Distinguished Papers of Display Week 2017

As of this year, all **Distinguished Papers** (DP) of the SID Symposium have a **peer reviewed expanded version** published in **JSID.** In fact, passing peer review is now a prerequisite for achieving the DP status, adding to the importance of the recognition and increasing the worldwide visibility and availability of these papers.
A **virtual JSID issue** containing the 20 Expanded Distinguished Papers is **openly accessible** until December 31st at **http://tinyurl.com/edpdw17**.

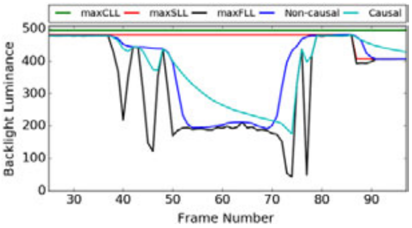
Highlighted recent papers

Power saving through state retention in IGZO-TFT AMOLED displays for wearable applications | Soeren Steudel *et al.*| DOI: 10.1002/jsid.544



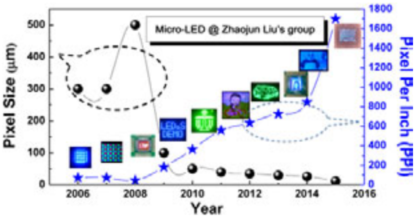
By using an IGZO thin-film transistor in a flexible active-matrix organic light-emitting diode display and leveraging the extremely low off current, we can switch off the power to the source and gate driver while maintaining the image unchanged for several minutes. Depending on the image content, low-refresh operation yields reduction in power consumption of up to 50% compared with continuous operation.

Efficacy of global dimming backlight and high-contrast liquid crystal panel for high-dynamic-range displays | Mina Choi and David M. Hoffman.| DOI: 10.1002/jsid.549



We evaluated the visual quality of challenging high-dynamic-range content with dramatic brightness changes presented on global dimming displays and how they compare with local dimming displays. We demonstrate that high native panel contrast allows most content to be shown with minimal artifacts associated with dynamic backlight control.

Fully-integrated active matrix programmable UV and blue micro-LED display system-on-panel (SoP) | Ke Zhang *et al.*| DOI: 10.1002/jsid.550



Micro-LEDs have been developed for more than a decade by Prof. Zhaojun Liu's group. We report a fully integrated active matrix programmable micro-LED system on panel (SoP) with ultraviolent (UV) and blue emission wavelengths. The micro-LED SoP has a resolution of 60 × 60 and pixel pitch of 70 μm with fully integrated scan and data circuits.

Information about the Journal

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Please direct any questions about the journal to the Editor-in-Chief of JSID at **editor@sid.org**
EarlyView: accepted papers about to be published can be accessed online via **tinyurl.com/jsidev**

Display Week 2017 Daily Reports

Foveal rendering, high-resolution automobile lamps, flat-panel speakers – and friends – were only a few of the highlights that Information Display's *experts reported on from Display Week 2017 in Los Angeles.*

by *Information Display* Staff

Every year, *ID* magazine's ace reporters focus on specific areas of technology at Display Week, sharing their discoveries in daily blogs during the show. This is an invaluable service because, as we all know, one person can't take in everything that Display Week has to offer. It's best to divide and conquer.

We offer here a small sampling of our reporters' blogs (including one from *ID* Executive Editor Stephen Atwood) to give you a taste of the show. If these excerpts inspire you to read more, please do so at www.informationdisplay.org.

In the next issue of the magazine, we will feature full-length articles from this year's reporters – Achin Bhowmik, Karlheinz Blankenbach, Gary Feather, Tom Fiske, Steve Sechrist, and Ken Werner.

In the meantime, enjoy these sample blogs.

The Most Valuable Part of Display Week

By Tom Fiske

Display Week is about more than the biggest display, the highest contrast, or even the best technical paper. Among the most valuable parts of the week are the relationships – the new ones and the re-newed ones – as well as the opportunity to be involved, at many levels, in one of the most exciting technology fields around.

I've been attending SID's conferences since the early '90s, so I've been around long enough to legitimately reminisce about the good old days (yeah – I'm one of those guys). When I joined SID, the cathode ray tube was king (but nervously looking over its shoulder at ambitious usurpers); active addressing for super-twisted-nematic LCDs was going to preserve STN's relevance against the rising tide of a-Si AMLCD technology; and belt-worn pagers with reflective twisted-nematic displays were among the most popular mobile communication choices – if you even needed that sort of thing.

The conference, then popularly known as SID and since rebranded as Display Week, has developed into the premier event for hearing about and seeing (and touching) new display technology. You can attend the symposium and exhibition (Fig. 1); get up to speed on related fields from world-class experts at the short courses and seminars; and learn about the latest trends at the business, investors, and market-focus conferences.

Every time I go to Display Week, I go with the expectation of learning about new technology and application and business trends. My engineer and researcher friends attend technical sessions and meet with suppliers and customers; the business folks go to make deals; and the marketers have the opportunity to pitch their latest wares and check out the competition. Of course, we all network. But in addition to the technology, business, and

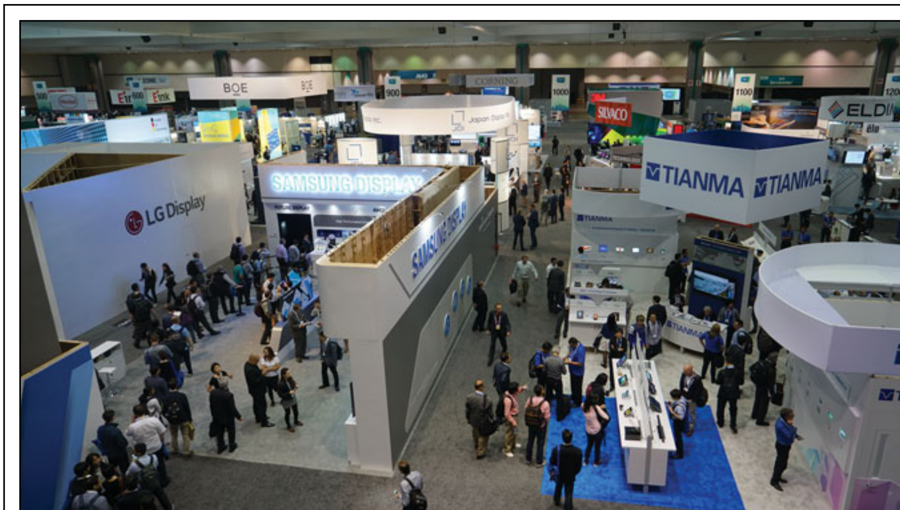

***Fig. 1:** The show floor at Display Week always features many discoveries.*

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market-centric events, there are the educational opportunities and display industry support activities – all those "soft" activities that are difficult to quantify for the bottom line. The short courses, seminars, forums, standards meetings, and other events provide an invaluable service to the display community by making space for learning and building the infrastructure necessary for the future of the industry.

As a volunteer over the years, I've had the unique privilege to peer "under the hood" at some aspects of SID's business and conference formation, as well as its display standards support. There are the usual eccentric personalities to contend with and struggles to get volunteers to follow through on commitments, but all in all, I've had a great time, learned a lot, and made some very valuable friendships. These are some of the most exceptional and talented people I have ever spent time with. I have worked with many (some at multiple companies), served booth duty with them, been their customers, written papers with them, and traded war stories with them. I have given and received job leads. I appreciate those relationships formed over time, even though I see my "SID friends" only once or twice a year. I remember fondly the ones who have passed on, and take comfort with those who remain.

So take this as a personal recommendation from me. If you didn't attend Display Week this year, start planning your strategy to get here next year. Get involved with SID at the local level; volunteer; write and submit good papers; take advantage of the learning opportunities; and attend the seminars, the symposium, and the exhibition. Above all, make friends for a lifetime.

Pixels, Pixels, and More Pixels

By Achin Bhowmik

"How many pixels are really needed for immersive visual experiences with a virtual reality (VR) head-mounted display (HMD)?" This was one of the most frequent questions I heard during and after the short course I taught at this year's Display Week.

So I thought I would reflect on this a bit, and point to some recent developments and trends in the display industry as gleaned from the presentations and demonstrations at this year's event.

First, let's consider some basic, back-of-an-envelope math and calculations. Here are some facts related to the human visual system. An ideal human eye has an angular resolution of about 1/60th of a degree at the central vision. Each eye has a horizontal field-of-view (FOV) of ~160° and a vertical FOV of ~175°. The two eyes work together for stereoscopic depth perception over ~120° wide and ~135° high FOV.

Since the current manufacturing processes for both liquid-crystal displays (LCDs) and organic light-emitting diode displays (OLEDs) produce a uniform pixel density across the entire surface of the spatial light modulators, the numbers above yield a whopping ~100 megapixels for each eye and ~60 megapixels for stereo vision.

While this would provide perfect 20/20 visual acuity, packing such a high number of pixels into the small screens in a VR HMD is obviously not feasible with current technologies. To put this into context, the two displays in the HTC Vive HMD contain a total of 2.6 megapixels, resulting in quite visible pixilation artifacts. Most course participants raised their hands in response to a question about whether pixel densities in current VR HMDs were unacceptable (I suspect the rest agreed but were too lazy to raise their hands!).

Even if it were possible to make VR displays with 60 million to 100 million pixels, other system-level constraints would make it impractical. One is the large amount of graphical and computational resources necessary to create enough polygons to render the visual richness to match such high-pixel density on the screens. Next, the current bandwidth capabilities cannot support the transport of such enormous amounts of data among the computation engines, memory devices, and display screens, while at the same time meeting the stringent latency requirements for VR.

So … is this a dead end? The answer is a resounding "no!" Challenges such as these are what innovators and engineers live for! Let's look at biology for some clues. How does the human visual system address this dilemma? It turns out that high visual acuity for humans is limited to a very small visual field – about +/- 1° around the optical axis of the eye, centered on the fovea. If we could track the user's eye gaze in real time, we could render a high number of polygons in a small area around the viewing direction and drop the number exponentially as we move away from it. Graphics engineers have a term for such technologies already in exploration – "foveated" or "foveal" rendering. This would drastically reduce the graphics workload and associated power consumption problems.

Clearly, we are still in the early days of VR, with many challenges remaining to be solved, including presenting adequate visual acuity on displays. This is an exciting time for the display industry and its engineers, reminiscent of the days at the onset of revolutionary display discoveries for high-definition televisions (HDTVs) and smartphones.

How About a 40-Megapixel Smartphone?

By Stephen P. Atwood

In an excellent keynote address at Display Week, "Enabling Rich and Immersive Experiences in Virtual and Augmented Reality," Google's Clay Bavor discussed several aspects of his company's strategy to develop immersive VR/AR applications and enabling hardware. Google has rather firmly focused its efforts on an architecture that utilizes commercially available smartphones. Though Bavor mentioned dedicated VR headset development and showed one image of a notional device, overall the company is concentrating on making smartphones work for VR applications.

There are challenges, including latency and resolution. Latency creates a discontinuous experience during head movement, and resolution limitations create effects similar to having poor vision in real life. Both of these challenges can be addressed, as Bavor explained, but what really got my attention was his announcement that Google and an unnamed partner have developed a smartphone display with 20-megapixel resolution per eye! That's presumably at least a 40-megapixel total display, and it's OLED-based as well. That's the good news.

The bad news is that in order to supply content to that device at the required frame rates of 90 to 120Hz, the raw data stream approaches 100 gb/sec. Yikes! That's not going to happen tomorrow, although high-performance video data compression is quickly becoming an option. This is described in the May/June issue of *Information Display*, which features the article "Create Higher Resolution Displays with the VESA DSC Standard." Maybe that's a path forward.

Google's path forward is to discuss what it calls "foveal rendering," which basically uses iris tracking to determine where your eye is focused, then renders a small region in the center of your vision at full resolution. The rest of the scene is rendered at lower resolution. Presumably, if you looked at the same space long enough, the rest of the periphery would also fill in at high resolution. Bavor also alluded to the need for an algorithm that could anticipate where your eye would be moving, akin to how a surfer anticipates a coming wave and gets up to speed as the crest arrives. Similarly, any algorithm performing this type of advanced processing would presumably need to anticipate what the observer is going to do; otherwise, the reaction time and subsequent latency would ruin the magic of the experience.

Whether this approach achieves commercial viability in the near future or not, it's exciting to think about the various challenges that were overcome to make even a few prototypes at this resolution, and how this furthers the very high pixel-density capabilities already in place. It's clearly an exciting target with a killer application. Time to start paddling – the next wave is coming.

I-Zone: Innovation in Light and Sound

By Ken Werner

The Innovation Zone (I-Zone) at SID Display Week 2017 featured approximately 50 exhibitors, more than double the average of years past. Among the genuine innovations on display at the I-Zone was the high-resolution, automobile headlamp, 30,000-pixel LCD shutter shown by the University of Stuttgart and automotive lighting company Hella. The light pattern of the headlamp can be controlled with great flexibility, and can be integrated with a car's GPS and situational awareness systems.

Another intriguing innovation was presented by the gaming headphone maker Turtle Beach (in conjunction with Nepes Display). Its HyperSound transparent, flat-panel loudspeakers (Fig. 2) work on a different principle than the old NXT speakers, whose technology has been adapted by LG and Sony in their current high-end OLED TVs.

Turtle Beach's speakers are capacitive, and the vibrating layers are driven by two signals; the first is 100 kHz and the second is 100 kHz plus the audio sideband. The result, as explained by Turtle Beach's rep, is that the audio portion of the signal is constructed in the space in

Fig. 2: *Turtle Beach (in conjunction with Nepes Display) was named an I-Zone honoree for its flat-panel speakers. Photo courtesy of Ken Werner.*

front of the speakers. The effect is startling, with two speakers able to construct a surround-sound field of remarkable clarity and precise location of sounds. Another characteristic is that the sound field is highly directional and cannot be heard even 10 degrees or so off axis. Turtle Beach is currently field-testing the technology in kiosks, and is looking for manufacturing and application partners.

Digital Signage Is a Quiet Giant of the Display Industry

By Gary Feather

The digital signage (DS) sessions at Display Week opened with discussions of the market aspects of the technology, and followed with descriptions of how the displays are being implemented. The general consensus was that display innovations will grow the DS market over $1 billion annually in just two years.

The target markets now and in the future are overwhelming. Worldwide business and technology markets discussed at Display Week included:

- Sports venues and public arenas
- Las Vegas and gaming (sports books and entertainment)
- Transportation (trains and planes)
- Government (command, control, communications, and information)
- Retail and digital out of home (DOOH)
- Corporate and conferencing
- Interactive and augmented reality entertainment performers in the AR environment with huge audiences
- Cinema, to replace digital light processing (DLP) projection

Many in the industry don't realize that DS display solutions account for billions of dollars in sales. Signage includes the special (and often artistic) implementation of LCD panels; LCD-tiled walls measuring hundreds of square feet; OLED panels with unique image quality; and LED-based, seamless tiled panels of any shape, size, and pixel pitch. Digital signage is currently exploiting all the developments of the display industry to give consumers unique and valued visualization solutions. ■

THE DISPLAY INDUSTRY'S SOURCE
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2017 Editorial Calendar

Issue	Editorial Coverage	Ad Closing Date
January/February	**Applied Vision** **Special Features:** Reducing Stereoscopic Artifacts, Realizing Augmented and Virtual Reality, New Display Frontiers, Cool New Devices for a New Year **Markets:** Game developers, medical equipment manufacturers, research institutions, OEMs, software developers, wearable designers, entertainment industry research and developers	**December 28**
March/April	**Display Week Preview, Display Materials** **Special Features:** SID Honors and Awards, Symposium Preview, Display Week at a Glance, MicroLEDs, Progress in OLED Manufacturing, Disruptive Materials, Nine Most Important Display Trends from CES **Markets:** OEMs, deposition equipment manufacturers, entertainment industry research and developers, display and electronic industry analysts	**February 27**
May/June	**Display Week Special, Automotive Displays** **Special Features:** Display Industry Awards, Products on Display, Key Trends in Automotive Displays, Head-up Designs for Vehicles, Novel Interfaces for Automobiles **Markets:** Consumer products (TV makers, mobile phone companies), OEMs, research institutes, auto makers, display module manufacturers, marine and aeronautical companies **Bonus Distribution: Display Week 2017 in Los Angeles**	**April 18**
July/August	**Wearable, Flexible Technology and HDR & Advanced Displays** **Special Features:** Flexible Technology Overview, Advanced Displays Overview, Wearables Round-up, Overcoming HDR Challenges **Markets:** Research institutions, OEMs, OLED process and materials manufacturers, entertainment industry research and development, measurement systems manufacturers	**June 16**
September/ October	**Display Week Wrap-up, Digital Signage** **Special Features:** Display Week Technology Reviews, Best in Show and Innovation Awards, Digital Signage Trends, Ruggedization Challenges for Digital Signage **Markets:** Large-area digital signage developers; in-store electronic label manufacturers, advertising and entertainment system developers, consumer product developers, retail system developers	**August 22**
November/ December	**Light-field and Holographic Systems** **Special Features:** Real-world light-field applications, holographic approaches, solving problems of next-generation displays **Markets:** OEMs, Consumer product developers, research institutes, auto makers, entertainment and gaming developers; measurement systems manufacturers	**October 20**

Q&A with Dick McCartney of Pixel Scientific

ID magazine interviews Dick McCartney, CEO of Pixel Scientific, a company with a new name and a rich heritage. Until recently, Pixel Scientific was Tannas Electronic Displays, founded in 1999 by display visionary and pioneer Larry Tannas. In late 2015, McCartney and fellow investors bought the company from Tannas, and are carrying on with its custom display-sizing technology and license portfolio management, while also branching out to new areas. Before acquiring Pixel Scientific, McCartney was director of technology creation for Samsung Display in the US. He is a fellow of SID and has held many offices within the Society for Information Display, including general chair and program chair.

Based on written commentary by Dick McCartney and interview conducted by Jenny Donelan

Information Display:
What's the history behind Tannas Electronic Displays and Pixel Scientific?

Dick McCartney:
About 18 years ago, Larry Tannas [founder of Tannas Electronic Displays] realized that he could serve a need that had emerged for custom-sized LCDs. Quality LCDs were only being made offshore – there wasn't an adequate domestic supply – and this was a big concern at the time for the US military. Larry came across a cracked LCD that still worked on one side of the crack. As he thought about why it would still partially work, the seeds of invention were planted. He began to envision that one way to obtain special-sized displays was to excise a smaller display from a bigger one, and this approach enabled his custom-sized remanufacturing.

Customers need custom-sized or special-sized displays for various reasons. At the heart of our business is the fact that LCDs are very expensive to make. They require billion-dollar factories, and the very high start-up costs for a new design must be amortized over a long run. So LCD companies generally only make high-volume displays, which largely go to the consumer electronics market: TVs, monitors, tablets, phones, and notebooks. It's from that base, then, that we obtain those "blanks," as do our licensees. That's how we can furnish a relatively lower volume and substantially higher value for industries including aviation and aviation simulation, the digital signage market, the medical market, and others.

***Jenny Donelan** is the editor in chief of* Information Display *Magazine. She can be reached at jdonelan@pcm411.com.*

ID: There aren't many other companies that do this, are there?

DM: We have the basic patents, but we have created a significant industry through licensing of that intellectual property. So no, not very many, but there are a handful of licensed companies throughout the world, including several in Asia and Europe as well as the US. All of our licenses are limited in some way, either into specific applications or geographies, or for embedding into a company's own system-level products. We are the only company that can produce in all markets and geographies.

ID: How did you become involved with the company?

DM: Nearly all my career has been in displays in general and LCDs in particular. I did some seminal work in LCDs in electronics, optics, and LCD subpixel construction in the early 1990s while developing LCDs for the Boeing 777 airplane. LCDs were not at all ready for aircraft applications at that time, and we had to invent several new technologies. Many of those have found their way into consumer-market products today. Larry was familiar with my background, and a few decades or so ago, he invited me to teach a section in the LCD course he had organized through UCLA. Over the course of time, as his custom-display business grew, Larry would contact me to see if I could help him with special projects or to figure out something that wasn't working. So as a consultant, on nights and weekends, I would work to identify solutions. I became very familiar with the excising process and thought it had a lot of merit.

The opportunity came along to buy into the company when Larry wanted to retire, and so I raised my own money together with some from an investment group, and we purchased the

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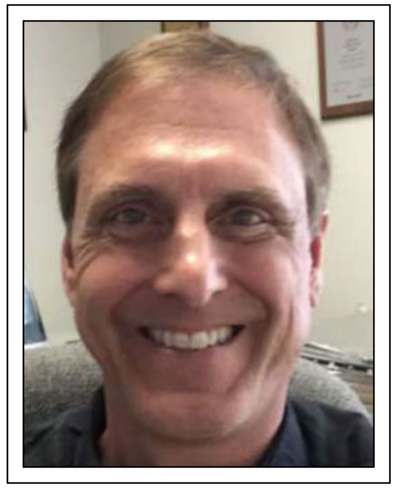
majority share of what was then Tannas Electronic Displays, or TED. I became CEO and renamed the company Pixel Scientific. I also moved the company and a key production technician from Orange County in the LA area to a leased office and factory in Scotts Valley, so we are now part of Silicon Valley. We are a modestly small company, with four direct employees at the moment. But we have off-shore contract manufacturing as well as contract optical, electrical, and mechanical design engineering and a cadre of consultants, so we command a lot more individual effort than we have directly employed. The contract manufacturing and engineering has really enabled us to take on more and new business quickly. It also gives us the opportunity to gradually grow the company in a controlled and profitable way as we choose what to bring in-house.



Dick McCartney

I think there's a lot of opportunity going forward that I'm very excited about. As I look around the world of displays, it isn't shrinking but growing. There are a lot of opportunities that do not have solutions yet, and I think that we're gearing up with new technology to bring solutions.

ID: Is the corporate culture different from what you were used to?

DM: I was previously with Samsung, and with National Semiconductor/Texas Instruments before that. They were very large corporations where primarily my focus was in near- and long-term research. I also worked for Honeywell in aerospace doing technology development, as well as having been part of three start-ups, one of which was how I came to National Semiconductor. So I have worked in both the start-up environment and for some pretty large technology companies. I feel I know the benefits and limitations of a small technology company. Large corporations have the staying power to spend what is needed to succeed and survive a few missteps. Small companies like ours need to invest frugally and be careful to stay focused on the right technologies. Although we are doing some of that longer-term research right now at Pixel Scientific, it is certainly a different environment than my large-company experience in that we are closer to the customers and their immediate demands, and I personally am much closer to operations than I have been in the past. Our plan, though, is to grow and position the company to fully fund new advancements in display technology.

That is the history, or culture, if you will, that we inherited, and it is the strategy for our future success. Technology companies large or small cannot rest. That is why I chose to buy the company and to leverage the core competency we have into new competencies and new classes of display products. We are standing on the shoulders of an established company, but are looking forward with an entrepreneurial mindset.

ID: In terms of the immediate future, where is LCD resizing most important now? What's the major market? And going forward, what's the focus for the diversification you mentioned?

DM: The dominant areas right now are in digital signage, and that includes transportation signage and the gaming industry. It surprised me to learn how many licensed displays are part of gaming machines – all the machines you see in Las Vegas, for example. Looking forward, you also see a lot of displays in automobiles these days, and it's becoming very commonplace to see those displays in forms other than rectangles. We have made prototypes for automotive concept cars, and that has given us some insight into that future. So we are looking at technologies that enable those kinds of opportunities.

The aircraft industry is particularly important to us. The physical constraints of instrument panels make custom-sized displays essential. We supply heavily into the aircraft simulation space, and we have some displays flying on aircraft today. But a growth area for us is in winning more flight displays. I believe strongly that a properly engineered and manufactured, excised LCD using our proprietary sealing process is as robust as any custom designed LCD. Since the takeover, we have gained a growing reputation for quality and depth of engineering and we are getting the attention of avionics manufacturers. In fact, we have won our first large-scale production program in avionics, although it is with a standard-sized LCD and not custom sized. But we have several opportunities in process, and I am certain we will soon win a volume-order flight display opportunity with a custom-sized display. We are taking the right steps. We have added NVIS capability, heater glass, and anti-reflective cover glass to our offerings in both flight and flight-simulation hardware. Overall, the display industry is moving to new sizes and new formats, and fitting into new spaces, and I think that's where our technology comes in.

In addition, as I said, we are not just a custom-sized-LCD supplier. We are now a total-solution-display supplier, offering whole modules. And this has allowed us to add value like high brightness, better viewing angles, larger color envelopes, better

> **"Litigation is very expensive for both parties. Often it is far better to create partners than fight adversaries."**

color matching, and other technologies. We have customers for whom we offer both a standard display and a custom-sized display for the same flight deck, for example. Our business is becoming much broader, and this is a difference. TED focused exclusively on custom sizes and was largely a service business. The customer furnished the original display, and TED provided the service of excising a smaller display from it in open cell form. Certainly, the custom sizes and service are a core part of our business, but we are now a display-technology supplier with both custom-sized and standard-sized display products, which is why we picked the name Pixel Scientific. We're taking the technology that we have, augmenting it, and pushing ourselves into places where others couldn't go before.

> **"Technology companies large or small cannot rest."**

ID: What is the size of the marketplace for resized LCDs, and what are/have been the volumes?

DM: It is a bit difficult for us to accurately estimate the size of the worldwide market for our excised displays because we have limited access to the businesses of several of our key licensees. I can put a little perspective on it in terms of market size by dollars. Keep in mind, though, that average selling prices can vary substantially given other factors such as backlight brightness and the ruggedizing needed for things like the outdoor environment. But I estimate the aerospace simulator market is about $6 million and flight displays are about $160 million. Digital signage worldwide, including specialty displays like those in gaming machines, is about $120 million and growing rapidly. This growth has prompted some OEMs to introduce what they call stretched displays, which are designed specifically for digital signage. The OEMs' entry, first of all, only helps expand the market, which is good, of course. But we and our licensees are quite happy to buy a native display and add the value of brightness and ruggedization to it. There are virtually no customers in the digital signage market for open cells. All of our licensees are providing custom modules. Excising allows them and us to offer a broader range of sizes than otherwise would be possible.

ID: How many steps are involved in the LCD resizing process, and what are the yields like?

DM: Well, I can't really talk about yields other than to say that they are quite high. The process is heavily automated at virtually all of our licensees, certainly all that are doing large volumes. It has to be automated to service the signage market. That automation assures consistency. Yield losses are much more related to handling errors and equipment failures than variations in the excise process itself.

As for the steps, I don't think I want to dive too heavily into the details here, but I do want to separate out a few elements in both the glass and the electronics. The largest part of what determines at what column or at what row a display can be cut is the location of the row and column drivers; you must go between them, of course. But just that alone is not the whole story. A significant part of the effort can involve re-engineering the attached circuit boards. If you are shortening a display, generally you want to shorten the attached circuit board too. That can involve a good bit of reverse engineering to determine if and where to cut the board and how to restore functions that would be lost in removing a part of the printed circuit board. As the industry has gotten more sophisticated – moving to multilayered boards, for example – techniques like X-raying to map out traces are needed. Then techniques like designing a custom flex board to reattach, say, the cut-away piece of the circuit, but in a different place, are needed. So it isn't just about cutting glass. It takes a good bit of competency in LCD electronics in order to produce a design.

In terms of the glass-cutting itself, there are some critically important steps. The seal in particular is very important. The LCD seal does a few jobs and the replacement seal needs to do the same, as well as or better than the original seal. One of the jobs is to keep oxygen, water, and other molecules out of the liquid crystal. Another is to keep the liquid crystal in, of course. But the seal also provides proper spacing between the glass plates at the edge, as well as providing high compression and tension strength (including adhesion strength) to maintain integrity through pressure, temperature, and bending variations. What's more, no air bubbles can be trapped inside the liquid crystal in the sealing process. So the seal is a significant piece. Our seal has survived the rigorous testing needed for flight displays. That's not easy.

ID: Have your techniques had to change with different backlighting or LCD technologies? Do they affect your processes?

DM: They do. We have had to adapt to changes in backlighting and also in the LCDs themselves. Things that are changing include the display glass thickness and the cell gaps becoming thinner. Techniques that worked before need refinement. The biggest change in backlighting has been the move to LEDs. Beyond those changes, at the mechanical level, subpixel electrodes are getting closer together because of higher resolutions. This also puts pressure on our technology because the feature sizes require new precision and we have had to adapt. As we offer whole modules, we need a custom-sized backlight too, and so we have been developing our own backlights.

As I said, LEDs are the big disruption in backlighting, and this works to our advantage, fortunately. LEDs make backlight design much easier. We outsource a lot of that work at the moment but are beginning to develop our own in-house capability. We have a partnership in which we design our own waveguides, and through that relationship, we have access to custom LEDs that emit in RGB bands rather than conventional white LEDs, which are broad-spectrum sources. That means we can

(continued on page 38)

SID 2018 honors and awards nominations

On behalf of the SID Honors and Awards Committee (H&AC), I am appealing for your active participation in the nomination of deserving individuals for the various SID honors and awards. The SID Board of Directors, based on recommendations made by the H&AC, grants all the awards. These awards include six major prizes awarded to individuals, not necessarily members of SID, based upon their outstanding achievements. The **Karl Ferdinand Braun prize** is awarded for ***"Outstanding Technical Achievement in, or Contribution to, Display Technology."*** The prize is named in honor of the German physicist and Nobel Laureate Karl Ferdinand Braun who, in 1897, invented the cathode-ray tube (CRT). Scientific and technical achievements that cover either a wide range of display technologies or the fundamental principles of a specific technology are the prime reasons for awarding this prize to a nominee. The **Jan Rajchman prize** is awarded for ***"Outstanding Scientific and Technical Achievement or Research in the Field of Flat-Panel Displays."*** This prize is specifically dedicated to those individuals who have made major contributions to one of the flat-panel-display technologies or, through their research activities, have advanced the state of understanding of one of those technologies. The **Otto Schade prize** is awarded for ***"Outstanding Scientific or Technical Achievement in the Advancement of Functional Performance and/or Image Quality of Information Displays."*** This prize is named in honor of the pioneering RCA engineer Otto Schade, who invented the concept of the Modulation Transfer Function (MTF) and who used it to characterize the entire display system, including the human observer. The advancement for this prize may be achieved in any display technology or display system or may be of a more general or theoretical nature. The scope of eligible advancement is broadly envisioned to encompass the areas of display systems, display electronics, applied vision and display human factors, image processing, and display metrology. The nature of eligible advancements may be in the form of theoretical or mathematical models, algorithms, software, hardware, or innovative methods of display-performance measurement and image-quality characterization. Each of these above-mentioned prizes carries a $2000 stipend.

SID honors and awards nominations

Nominations are now being solicited from SID members for candidates who qualify for SID Honors and Awards.

- KARL FERDINAND BRAUN PRIZE. Awarded for an outstanding *technical* achievement in, or contribution to, display technology.
- JAN RAJCHMAN PRIZE. Awarded for an outstanding *scientific* or *technical* achievement in, or contribution to, research on flat-panel displays.
- OTTO SCHADE PRIZE. Awarded for an outstanding *scientific* or *technical* achievement in, or contribution to, the advancement of functional performance and/or image quality of information displays.
- SLOTTOW–OWAKI PRIZE. Awarded for outstanding contributions to the education and training of students and professionals in the field of information display.
- PETER BRODY PRIZE. Awarded to honor outstanding contributions of young researchers (under age 40) who have made major-impact technical contributions to the developments of active-matrix-addressed displays.
- LEWIS AND BEATRICE WINNER AWARD. Awarded for exceptional and sustained service to SID.
- FELLOW. The membership grade of Fellow is one of unusual professional distinction and is conferred annually upon a SID member of outstanding qualifications and experience as a scientist or engineer in the field of information display who has made widely recognized and significant contribution to the advancement of the display field.
- SPECIAL RECOGNITION AWARDS. Presented to members of the technical, scientific, and business community (not necessarily SID members) for distinguished and valued contributions to the information-display field. These awards may be made for contributions in one or more of the following categories: (a) outstanding technical accomplishments; (b) outstanding contributions to the literature; (c) outstanding service to the Society; (d) outstanding entrepreneurial accomplishments; and (e) outstanding achievements in education.

Nominations for SID Honors and Awards must include the following information, preferably in the order given below. Nomination Templates and Samples are provided at *www.sid.org/awards/nomination.html.*

1. Name, Present Occupation, Business and Home Address, Phone and Fax Numbers, and SID Grade (Member or Fellow) of Nominee.

2. Award being recommended:
   Jan Rajchman Prize
   Karl Ferdinand Braun Prize
   Otto Schade Prize
   Slottow–Owaki Prize
   Peter Brody Prize
   Lewis and Beatrice Winner Award
   Fellow*
   Special Recognition Award

*Nominations for election to the Grade of Fellow must be supported in writing by at least five SID members.

3. Proposed Citation. This should not exceed 30 words.

4. Name, Address, Telephone Number, and SID Membership Grade of Nominator.

5. Education and Professional History of Candidate. Include college and/or university degrees, positions and responsibilities of each professional employment.

6. Professional Awards and Other Professional Society Affiliations and Grades of Membership.

7. Specific statement by the nominator concerning the most significant achievement or achievements or outstanding technical leadership that qualifies the candidate for the award. This is the most important consideration for the Honors and Awards committee, and it should be specific (citing references when necessary) and concise.

8. Supportive material. Cite evidence of technical achievements and creativity, such as patents and publications, or other evidence of success and peer recognition. Cite material that specifically supports the citation and statement in (7) above. (Note: the nominee may be asked by the nominator to supply information for his candidacy where this may be useful to establish or complete the list of qualifications).

9. Endorsements. Fellow nominations must be supported by the endorsements indicated in (2) above. Supportive letters of endorser will strengthen the nominations for any award.

E-mail the complete nomination – including all the above material – by **October 15, 2017** to swu@ucf.edu with cc to office@sid.org or by regular mail to:
Shin-Tson Wu, Honors and Awards Chair, Society for Information Display,
1475 S. Bascom Ave., Ste. 114, Campbell, CA 95008, U.S.A.

The **Slottow–Owaki prize** is awarded for ***"Outstanding Contributions to the Education and Training of Students and Professionals in the Field of Information Display."*** This prize is named in honor of Professor H. Gene Slottow, University of Illinois, an inventor of the plasma display and Professor Kenichi Owaki from the Hiroshima Institute of Technology and an early leader of the pioneering Fujitsu Plasma Display program. The oustanding education and training contributions recognized by this prize is not limited to those of a professor in a formal university, but may also include training given by researchers, engineers, and managers in industry who have done an outstanding job developing information-display professionals. The Slottow–Owaki prize carries a $2000 stipend.

The **Peter Brody Prize** is awarded to honor ***"Outstanding contributions of young researchers (under age 40) who have made major-impact technical contributions to the developments of active-matrix-addressed displays"*** in one or more of the following areas:

- Thin film transistor devices
- Active matrix addressing techniques
- Active matrix device manufacturing
- Active matrix display media
- Active matrix display enabling components.

The award is made by the Board of Directors acting on the recommendation of the Honors and Awards Committee and carries a stipend of US $2000.

The sixth major SID award, the **Lewis and Beatrice Winner Award,** is awarded for ***"Exceptional and Sustained Service to the Society."*** This award is granted exclusively to those who have worked hard over many years to further the goals of the Society.

The membership grade of **SID Fellow** is one of unusual professional distinction. Each year the SID Board of Directors elects a limited number (up to 0.1% of the membership in that year) of **SID members** in good standing to the grade of **Fellow.** To be eligible, candidates must have been members at the time of nomination for at least 5 years, with the last 3 years consecutive. A candidate for election to Fellow is a member with ***"Outstanding Qualifications and Experience as a Scientist or Engineer in the Field of Information Display who has made Widely Recognized and Significant Contributions to the Advancement of the Display Field"*** over a sustained period of time. SID members practicing in the field recognize the nominee's work as providing significant technical contributions to knowledge in their area(s) of expertise. For this reason, five endorsements from SID members are required to accompany each Fellow nomination. Each Fellow nomination is evaluated by the H&AC, based on a weighted set of five criteria. These criteria and their assigned weights are creativity and patents, 30%; technical accomplishments and publications, 30%; technical leadership, 20%; service to SID, 15%; and other accomplishments, 5%. When submitting a Fellow award nomination, please keep these criteria with their weights in mind.

The **Special Recognition Award** is given annually to a number of individuals (membership in the SID is not required) of the scientific and business community for distinguished and valued contribution in the information-display field. These awards are given for contributions in one or more of the following categories: (a) ***Outstanding Technical Accomplishments,*** (b) ***Outstanding Contributions to the Literature,*** (c) ***Outstanding Service to the Society,*** (d) ***Outstanding Entrepreneurial Accomplishments,*** and (e) ***Outstanding Achievements in Education.*** When evaluating the Special Recognition Award nominations, the H&AC uses a five-level rating scale in each of the above-listed five categories, and these categories have equal weight. Nominators should indicate the category in which a Special Recognition Award nomination is to be considered by the H&AC. More than one category may be indicated. The nomination should, of course, stress accomplishments in the category or categories selected by the nominator.

While an individual nominated for an award or election to Fellow may not submit his/her own nomination, nominators may, if necessary, ask a nominee for information that will be useful in preparing the nomination. The nomination process is relatively simple, but requires that the nominator and perhaps some colleagues devote a little time to preparation of the supporting material that the H&AC needs in order to evaluate each nomination for its merit. It is not necessary to submit a complete publication record with a nomination. Just list the titles of the most significant half a dozen or less papers and patents authored by the nominee, and list the total number of papers and patents he/she has authored.

Determination of the winners for SID honors and awards is a highly selective process. On average, less than 30% of the nominations are selected to receive awards. Some of the major prizes are not awarded every year due to the lack of sufficiently qualified nominees. On the other hand, once a nomination is submitted, it will stay active for three consecutive years and will be considered three times by the H&AC. The nominator of such a nomination may improve the chances of the nomination by submitting additional material for the second or third year that it is considered, but such changes are not required.

Descriptions of each award and the lists of previous award winners can be found at *www.sid.org/About/Awards/IndividualHonorsandAwards.aspx*. Nomination forms can be downloaded by clicking on "click here" at the bottom of the text box on the above site where you will find Nomination Templates in both MS Word (preferred) and Text formats. Please use the links to find the Sample Nominations, which are useful for composing your nomination since these are the actual successful nominations for some previous SID awards. Nominations should preferably be submitted by e-mail. However, you can also submit nominations by ordinary mail if necessary.

Please note that with each Fellow nomination, only five written endorsements by five SID members are required. These brief endorsements – *a minimum of 2–3 sentences* to a maximum of one-half page in length – *must state why clearly and succinctly, in the opinion of the endorser, the nominee deserves to be elected to a Fellow of the Society. Identical endorsements by two or more endorsers will be automatically rejected* (no form letters, please). Please send these endorsements to me either by e-mail (preferred) or by hardcopy to the address stated in the accompanying text box. Only the Fellow nominations are required to have these endorsements. However, I encourage you to submit at least a few endorsements for all nominations since they will frequently add further support to your nomination.

All 2018 award nominations, including support letters, are to be submitted by October 15, 2017. E-mail your nominations directly to swu@ucf.edu with cc to office@sid.org. If that is not possible, then please send your hardcopy nomination by regular mail.

As I state each year: "In our professional lives, there are few greater rewards than recognition by our peers. For an individual in the field of displays, an award or prize from the SID, which represents his or her peers worldwide, is a most significant, happy, and satisfying experience. In addition, the overall reputation of the society depends on the individuals who are in its 'Hall of Fame.'

When you nominate someone for an award or prize, you are bringing happiness to an individual and his or her family and friends, and you are also benefiting the society as a whole."

Thank you for your nomination in advance.

— Shin-Tson Wu
Chair, SID Honors & Awards Committee ■

editorial

continued from page 2

Also busy in this area is a joint team at Kent State and Jiangnan University who together report on their work on thermally sensitive LCDs in "Developing Liquid-Crystal Functionalized Fabrics for Wearable Sensors." This work entails creating liquid-crystal capsules that can be embedded into a wide variety of fibers and films to create temperature-sensitive, color-changing ("thermochromic") materials that can be used for many purposes, including clothing, medical sensors, *etc*.

Our applications feature for this issue continues the core theme with a story about a new family of materials suitable for flexible-display substrates called polysulfide thermosetting polymers (PSTs). I say "new," but in fact this work has been in progress for more than 10 years, first destined for biomedical applications but now found to be very advantageous for display applications as an alternative to polyimide. PSTs enable transparency, solvent-free fabrication, very low surface roughness, and low-temperature processing, all at reduced total material cost – so say the authors Tolis Voutsas, *et. al.* from Ares Materials, Inc., in their article, "New Polymer Materials Enable a Variety of Flexible Substrates." I really like the possibilities discussed in this article and what they mean in terms of more options for the flexible-display materials infrastructure.

Our Market Insights focus this month is on a small but powerful company in our industry called Pixel Scientific, which until just recently was known as Tannas Electronic Displays, the founder of custom resizing technology for LCD glass. If you've ever seen uniquely sized LCD panels in cockpits of planes, in digital signs, or in industrial automation equipment, odds are they were custom sized from larger commercial panels using the Tannas patented technology developed by display visionary and pioneer Larry Tannas. In 2015 Dick McCartney (CEO) and fellow investors bought the company from Tannas, and now they are carrying on with its custom display-sizing technology and savvy portfolio management, while also branching out to new areas. Our own Jenny Donelan spoke with Dick about this endeavor and gained a wealth of insights about the company, its extensive patent portfolio, and the industry at large. Note especially Dick's comments about investing in intellectual property protection and the benefits it can bring to your business. We've published a number of articles in the past about IP development and the patent process. This continues to be one of the most critical areas of concern for technology developers and a properly executed strategy will pay many benefits for years to come.

We were all at Display Week just about a month ago (as of this writing) and while our expanded coverage is still in development, we figured we'd put in just a taste by publishing some of the best blogs that we developed and posted on-line during the event. And so, we offer a short compilation of some of the hot topics at the show, including foveal rendering, high-resolution automobile lamps, flat-panel speakers, very high-pixel-density phones, *etc.* from Display Week 2017 in Los Angeles. If you want to know more and were not there, stay tuned for our next issue with full coverage from all of our talented roving reporters.

Despite all the great things to work on inside the walls of your business, don't forget that we're in the middle of the summer and it's a great time to reset your work-life balance as well. Take time to enjoy the outdoors, spend more time with your family, and visit someplace you've never seen before. Rekindle old friendships and make new ones. It's shaping up to be a great summer, both inside and outside of our unique industry, and I wish you all good health and some much-deserved recreation as well. ■

guest editorial

continued from page 4

pressure, and other types of mechanical stress, as well as electrical, magnetic, and optical fields. Of course, integrating liquid crystals with fibers for wearable application is not easy. Many factors need to be considered: temperature range, adhesion to the fibers, and visual appearance, just to name a few. Overcoming many challenges, the team successfully developed thermochromic fabrics by bonding microcapsules of LC to fiber surfaces, or by fabricating coaxial fibers consisting of an LC core surrounded by a polymer sheath.

As shown in these three articles, significant progress has been made in stretchable displays in the past several years. Stretchable electrodes, interconnects, TFTs, and AMOLED displays have all been demonstrated. However, we are still facing the same challenge – how can we integrate this great technology into a device to make, dare to say, a stretchable device? The wearable sensor is a great idea – color-changing sensing for a color-dominant clothing application that requires no other components (not even electrodes). Alternatively, we need to develop applications that don't use many rigid components, or applications for which the rigid components can be hidden.

We can already stretch our displays; now let's try stretching our imaginations.

Ruiqing (Ray) Ma *is a member and past chair of the SID Flexible Display Committee, and currently serves as seminar chair for Display Week 2018. He can be reached at ruiqingm@gmail.com.* ■

continued from page 34

offer a much bigger color envelope straightforwardly without immediately turning to more sophisticated technology like quantum dots or direct RGB backlights, for example. These changes all give us the opportunity to innovate. We've had to adapt as we go along, and it's an important part of our ongoing portfolio of patents. We continue to add to it as we solve this or that problem.

ID: Speaking of your patent portfolio, it's our understanding that this aspect of the business has been quite successful.

DM: Larry was very wise to pursue the intellectual property to the extent that he did. He spent millions of dollars developing our patent portfolio, and it's pretty watertight. It's been defended and successfully vetted in the courts, and he was able to turn a substantial portion of the business into a licensing business, so a good portion of the revenue that we take in annually comes from royalties. And we continue to push that model forward as well, as we bring on new licensees. We are adding a few licensees in China. We are also in negotiations with places in Europe and other parts of Asia. Throughout this year I would project that we'll be closing several license deals.

The key thing I would say is that not every patent is a peer to every other. Some of them, of course, are just techniques, and those aren't the ones that you want to pursue with every dollar that you have because someone could maybe get around it, but there are fundamental patents that you should pursue and lock up. In other words, just having a patent isn't enough. You need to be able to claim the fundamentals somehow. Look, once you have an instance proof of just about anything useful, someone will find a way to duplicate it if it has any value at all. The advantage you have ordinarily is being first to the scene, so to speak, rather than more capable than anyone else. So the strategy is to have a watertight, fundamental patent, and a portfolio of patents, really, that force anyone who wants to duplicate what you have done to have to go through one of the doors you have patented.

Having said that, though, relying on patents to protect a business takes strategic planning. It is said that patents are a sport of kings. A small company can easily go broke trying to stop an infringer with deep pockets or frankly even not-so-deep pockets. Litigation is very expensive for both parties. Often it is far better to create partners than fight adversaries. Licensing can be an important tool in that way. And lastly I'd say that patents must be asserted. Otherwise, they won't be taken seriously. There has to be a sense that ignoring your IP will have consequences.

Larry did a brilliant job of creating an industry on the backbone of the patent portfolio. It's protected not only through the litigation but also by those who license it. They find people who may be infringing and we bring them into the fold one way or another. We're in the middle of an ongoing infringement case right now, and we continue to contact companies who might be infringing.

ID: So it's a combination of having something that is patentable on a fundamental level and then doing the work to protect it. Not all small businesses are quite this forward thinking.

DM: That's right, and there's another component to the licensing. When Larry came up with his technical solutions, he could have taken on the whole world and said, "All roads lead through me." And I think that is a common error that small companies make. They want to service the entire world. It's really hard to do. On the other hand, if you can take on a portion of that and license to others who want to take on other portions, you can grow from there and over time you can compete with those licensees and integrate further. Or you can form strategic partnerships with them. A rising tide lifts all boats, and that's an important business strategy when you have this kind of core technology. ■

continued from page 11

nanowires, carbon nanotubes and an elastomeric dielectric," *Nature Communications* **6**, 7647, 2015.
[13]J. Xu, S. Wang, G.-J. N. Wang, C. Zhu, S. Luo, *et al.*, "Highly stretchable polymer semiconductor films through the nanoconfinement effect," *Science* **355**, 59–64, 2017.
[14]F. Xu, M.-Y. Wu, N. S. Safron, S. S. Roy, R. M. Jacobberger, *et al.*, "Highly Stretchable Carbon Nanotube Transistors with Ion Gel Gate Dielectrics," *Nano Letters* **14**, 682−686, 2014.
[15]D. Kong, R. Pfattner, A. Chortos, C. Lu, A. C. Hinckley, *et al.*, "Capacitance Characterization of Elastomeric Dielectrics for Applications in Intrinsically Stretchable Thin Film Transistors," *Advanced Functional Materials* **26**, 4680–4686, 2016.
[16]M. S. Whitle, M. Kaltenbrunner, E. D. Glowacki, K. Gutnichenko, G. Kettlgruber, *et al.*, "Ultrathin, highly flexible and stretchable PLEDs," *Nature Photonics* **7**, 811–816, 2013.
[17]S. Ye, A. R. Rathmell, Z. Chen, I. E. Stewart, and B. J. Wiley, "Metal Nanowire Networks: The Next Generation of Transparent Conductors," *Advanced Materials* **26**, 6670–6687, 2016.
[18]J. Liang, L. Li, X. Niu, Z. Yu, and Q. Pei, "Elastomeric polymer light-emitting devices and displays," *Nature Photonics* **7**, 817–824, 2013.
[19]C. H. Yang, B. Chen, J. Zhou, Y. M. Chen, and Z. Suo, "Electroluminescence of Giant Stretchability," *Advanced Materials* **28**, 4480–4484, 2016.
[20]C. Larson, B. Peele, S. Li, S. Robinson, M. Totaro, *et al.*, "Highly stretchable electroluminescent skin for optical signaling and tactile sensing," *Science* **315**, 6277, 2016.
[21]T. Yokota, P. Zalar, M. Kaltenbrunner, H. Jinno, N. Matsuhisa, *et al.*, "Ultraflexible organic photonic skin," *Science Advances* **2**, 4, 2016.
[22]R.-H. Kim, D.-H. Kim, J. Xiao, B. H. Kim, S.-I. Park, *et al.*, "Waterproof AlInGaP optoelectronics on stretchable substrates with applications in biomedicine and robotics," *Nature Materials* **9**, 929–937, 2010.
[23]H. Ohmae, Y. Tomita, M. Kasahara, J. Schram, E. Smits, *et al.*, "Stretchable 45 × 80 RGB LED Display Using Meander Wiring Technology," *SID Symp. Digest of Tech. Papers*, 2015.
[24]J. Byun, B. Lee, E. Oh, H. Kim, S. Kim, *et al.*, "Fully printable, strain-engineered electronic wrap for customizable soft electronics," *Scientific Reports* **7**, 45328, 2017. ■

continued from page 15

[3]M. Xia, *et al.*, "Extremely stretchable all-carbon-nanotube transistor on flexible and transparent substrates," *Appl. Phys. Lett.* **105**, 143504-1-5, 2014.
[4]J. Liang, *et al.*, "Intrinsically stretchable and transparent thin-film transistors based on printable silver nanowires, carbon nanotubes and an elastomeric dielectric," *Nature Communication* **6**, 7647, 2015.
[5]T. Q. Trung, *et al.*, "An all-elastomeric transparent and stretchable temperature sensor for body-attachable wearable electronics," *Adv. Mater.* **28**, 502–509, 2015.
[6]J. Y. Oh, *et al.*, "Intrinsically stretchable and healable semiconducting polymer for organic transistors," *Nature* **539**, 411–415, 2016.
[7]F. Xu, *et al.*, "Highly stretchable carbon nanotube transistors with ion gel gate dielectrics," *Nano Lett.* **14**, 682–686, 2014.
[8]S. H. Chae, *et al.*, "Transferred wrinkled Al_2O_3 for highly stretchable and transparent graphene–carbon nanotube transistors," *Nature Materials* **12**, 403–409, 2013.
[9]K. Park, *et al.*, "Stretchable, transparent zinc oxide thin film transistors," *Adv. Funct. Mater.* **20**(20), 3577–3582, 2010.
[10]N. Münzenrieder, *et al.*, "Stretchable and conformable oxide thin-film electronics," *Adv. Electron. Mater*. **1**, 1400038-1-7, 2015.
[11]B. K. Sharma, *et al.*, "Load-controlled roll transfer of oxide transistors for stretchable electronics," *Adv. Funct. Mater*. **23**, 2024–2032, 2012.
[12]A. Romeo, *et al.*, "Stretchable metal oxide thin film transistors on engineered substrate for electronic skin applications," *Engineering in Medicine and Biology Society (EMBC)* 15584777, 8014–8017, 2015.
[13]J.-H. Hong, *et al.*, "9.1-inch stretchable AMOLED display based on LTPS technology," *JSID* **25**(3), 194–199, 2017.
[14]S. Yao, *et al.*, "Nanomaterial-enabled stretchable conductors: strategies, materials and devices," *Adv. Mater.* **27**, 1480–1511, 2015.
[15]K. Nomura, *et al.*, "Thin-film transistor fabricated in single-crystalline transparent oxide semiconductor," *Science* **300**, (5623), 1269–1272, 2003.
[16]Y. H. Kim, *et al.*, "Highly robust neutral plane oxide TFTs withstanding 0.25 mm bending radius for stretchable electronics," *Scientific Reports* **6**, 25734, 2016.
[17]A. Campo, *et al.*, "Modification of PDMS as a basis for surface wrinkle formation–chemical and mechanical characterization," *Polymer* **98**, 327–335, 2016.
[18]X. Li, *et al.*, "Stretchable Oxide TFTs for Wearable Electronics," *SID Symp. Digest of Tech. Papers* **48**(1), 42–45, 2017. ■

industry news

continued from page 3

extended temperature range and strengthened glass. Customers can also specify border color, legends, and logos.

Samsung Ships HDR Monitors for Gaming

Samsung Electronics America recently expanded its gaming portfolio with the ultra-wide, 49-in. CHG90 display and the 27- and 32-in. CHG70 monitors.

The CHG90 and CHG70 displays feature high-dynamic-range (HDR) picture enhancement technology that has until recently been reserved for televisions and large-format displays. They are designed to show games as developers intended them to be seen, dramatically improving picture quality and gameplay with crisper colors and sharper contrast.

The new monitors all leverage Samsung's "QLED" quantum-dot technology, which supports 125 percent of the sRGB color space and 95 percent of the DCI-P3 color space, for a wide range of accurate color reproduction — especially dark reds and greens — that stay crisp and clear even in bright light.

To enhance gameplay visuals further, the CHG70 joins the CHG90 as the industry's first gaming monitors to feature AMD's new Radeon FreeSync 2 technology. This functionality combines smooth, stutter- and tear-free gaming with low-latency, high-brightness, high-contrast visuals, as well as excellent black levels and support for a wide color gamut to show HDR content with twice the perceptible brightness offered by the sRGB standard.

The CHG90 has a 32:9 aspect ratio and 3,840 × 1,080 double-full HD (DFHD) resolution across an ultra-wide, 49-in. screen. The CHG90 also boasts a rapid 1-ms response time, 144Hz screen refresh rate, and advanced, four-channel scanning technology to deter motion blur throughout the entire screen, making the monitor ideal for first-person shooting, racing, flight simulation, and action-heavy games. ■

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kishibas@wiley.com

China Sales Office

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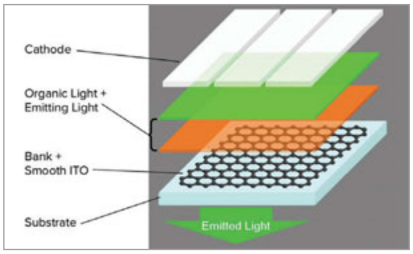

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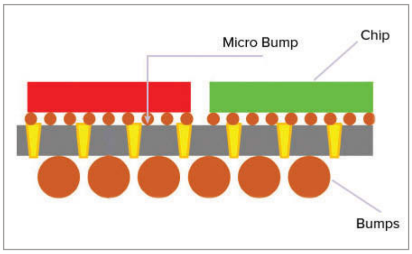

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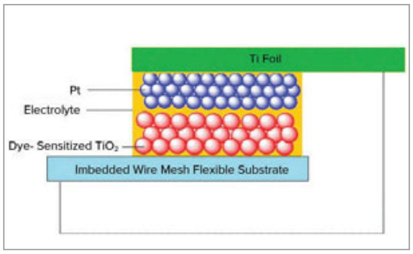

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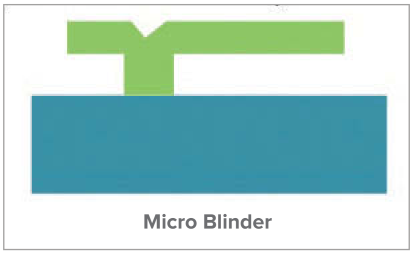

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Thin Film Devices Incorporated
1180 N. Tustin Avenue, Anaheim, CA 92807
Phone: 714.630.7127
Fax: 714.630.7119
Email: Sales@tfdinc.com

China Supply Chain:
Group International
jeanne-giil@hotmail.com

Korean Manufacturing:
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ion-tek@hanmail.net

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