FLEXIBLE AND WEARABLE TECHNOLOGY ISSUE

Information DISPLAY

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The New Wave of Flexible and Wearable Devices

Unlocking the Potential of Wearables

Wearables: From Whimsical to Necessary

Creating Displays for Mass-Produced Flexible Devices

Overcoming the Challenges of Foldable Displays

Plus:

Wearables Fill the Display Marketplace Void

Regional Business Report: Japan

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ON THE COVER: Some of the many concepts for wearable electronics that are making their ways into the marketplace are illustrated. Glasses, watches, patches, clothing, and even shoes are going electronic, and the applications they support can range from whimsical to highly sophisticated.

Cover Design: Jodi Buckley

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editorial

Here's to a Flexible New Year

by Stephen Atwood

It's 2015 and welcome to our first issue of *Information Display* in the New Year. I truly hope you all had a great restful holiday and are ready for whatever 2015 brings to our industry. This issue's focus is a combination of flexible displays and wearable electronics applications. We've been here before, having visited flexible display technologies last year at this time (remember the cuttlefish and electronic skin?) and before that in 2011 with stories about research into flexible LCDs and foldable backplanes. Each time we take on this topic we find more reasons to get excited, with the promise of the ultimate rollable/foldable display inching closer. However, the rollable display is not the only reason people are investing in flexible technology, and I would suggest that there are at least four main categories of advantages that flexible displays can bring to the party:

- *Ruggedization:* By making the display and associated elements flexible, the product becomes more rugged and unbreakable in normal use.
- *Curved and formable formats*: With flexibility, whether it is one-time forming or continuous bending, products such as smartphones, watches , and even car dashboards can be designed to be more accessible and user friendly.
- *Expanded screen sizes and content*: The most obvious opportunity is the ever-popular concept of a small device that fits in your pocket but then can be unfolded into a large-sized screen capable of full-HD resolution or beyond.
- *New and previously unrealizable product concepts*: The very nature of flexible technology suggests that traditional concepts of square, flat devices with front-facing touch screens can be shattered when the display itself is infinitely formable and flexible.

Most of the flexible-display product concepts discussed in the recent literature, including some in this issue, will leverage one or more of these intrinsic advantages. Consider LG's G Flex smartphone, for example. Largely heralded for its ability to resist breakage (including an impressive demonstration by *Consumer Reports* of its ability to withstand 1000 pounds of pressure), it also provides a natural curve that fits a user's face better than a flat phone. Back in 2011, we published an article discussing the concept of a new user interface where bending the display created an input to the user interface that would initiate actions like zooming or panning. ("A Flexible Display Enables a New Intuitive Interface," February 2011.) This and more innovation is surely on the way.

Of course, until the product designers of the future can get their hands on real production-level flexible displays, we will not know what feature elements truly take hold to become compelling to consumers, but we are already seeing that the marketplace is hungry to taste new things when the technology recipes are ready.

Also worth considering is the fact that "flexible" is just one part of a bigger category of technologies enabling all types of "wearables." Our cover this month provides a brief illustration of some of the many concepts for wearable electronics that are making their ways into the marketplace. Glasses, watches, patches, clothing, and even shoes are going electronic, and the applications they support can range from whimsical to highly sophisticated. Just consider the category of fitness tracking – close to 20 million devices in use today, and that number is predicted to triple in fewer than 5 years. We are already dependent on our cell phones on a daily basis. I think it's easy to believe we could be talked into carrying around a few more similar devices as long as they perform some useful or entertaining function. *(continued on page 36)*

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NEW PRODUCTS FOR A NEW YEAR

Sharp Offers 20.1-in. Display with 1400:1 Contrast Ratio

Sharp Microelectronics of the Americas (SMA) has a new 20.1-in.-diagonal LCD (Fig. 1). This panel offers extremely crisp images via a 1400:1 contrast ratio, making it perfect for viewing high levels of detail in most any ambient lighting situation. It also provides a drop-in replacement option in its size class for customers including manufacturers of medical, marine, and transportation products, among others.

Fig. 1: Sharp's new LCD panel for the medical/industrial market offers a 1400:1 contrast ratio.

NEC Makes a 84-in. UHD Display Optimized for Video Conferencing

NEC Display Solutions of America has announced an 84-in. ultra-high-definition (UHD) model designed to deliver exceptional picture clarity and four times the resolution of full HD (Fig. 2).

With a 3640 × 2160 native resolution, this display also supports the UHD resolution at 60 Hz through its DisplayPort connection. This means quick-moving content is displayed smoothly and makes the panel a good fit for video conferencing and command and control centers.

Fig. 2: NEC's new panel sports a 3640 × 2160 native resolution.

Canatu Introduces Stretchable Touch Film

Canatu, a manufacturer of flexible transparent conductive films and touch sensors, recently announced a new stretchable, formable, conductive film optimized for formed capacitive-touch displays and touch surfaces. CNB In-Mold Film is designed especially for automobile center consoles and dashboards, home appliance control panels, remote controls, smart watches, and portable electronic devices.

CNB In-Mold Film is stretchable up to and beyond 100% and can be formed and back-molded using standard industrial processes, which means that CNB touch sensors can be produced in almost any shape, from smooth spherical domes to sharp-edged casings with recesses and bulges. Possibilities include mechanical buttons in automotive dashboards, portable and wearable devices, washing machines, clothes dryers, dishwashers, ovens, and other appliances that can be enhanced with a robust water- and dust-proof 3-D-formed touch user interface.

4K Heads to Space

In the world of business, nothing speaks louder than a large infusion of cash, and with its investment in a rocket-launched satellite dedicated to broadcasting 4K last month, DirecTV has spoken.[1] With 4K content in short supply (Netflix and Amazon have begun streaming a limited amount of such content), industry participants from analysts to retail-store owners have been wondering if 4K can ever really take off. This major infrastructure investment by a satellite company does signal the likelihood that 4K will become mainstream, or at least that a very large company believes it will.

Although Internet streaming seems to have the current upper hand in terms of popularity, cable and satellite providers do control a relatively large delivery infrastructure by providing lots of bandwidth compared to Internet streaming. If these companies are willing to dedicate some of this bandwidth to 4K content, they can guarantee that consumers will get a predictable and reliable experience. It's a significant endorsement of the commercial value of 4K and a big step forward to providing consumers with a meaningful 4K experience. Of course, ESPN and DirecTV also backed 3-D TV and that effort fizzled, but most experts believe 4K has more staying power. DirecTV actually began Ultra-HD broadcasts in November 2014, but the new satellite will obviously support additional offerings for subscribers who have Ultra-HD televisions. *(continued on page 38)*

guest editorial

Get Ready for Another Form-Factor Revolution

by Ruiqing (Ray) Ma

I attended my first SID conference almost 20 years ago at the Walt Disney World Dolphin Hotel in Orlando. I still remember the first time I wandered out of the hotel during a session break. While walking along the palm-tree-covered walkway, admiring the 257-ft.-tall triangular tower and the two 56-ft.-tall dolphin statues atop the 12-story rectangular main building, breathing in the fresh tropical air blowing over a vast blue-colored lagoon, I was suddenly struck by a grand man-made white sandy beach in the middle of inland Florida – it was magical.

There was also something magical about the early 1990s for the display industry. It was a time when the flat-panel industry was just beginning to take off, and we enjoyed annual double-digit revenue growth and fast-paced innovations in both technology and application. The driving force behind this FPD revolution was mobility – effectively reducing the physical dimensions of displays from 3-D to 2-D. Notebook computers and portable consumer electronics demanded a thin form factor from displays.

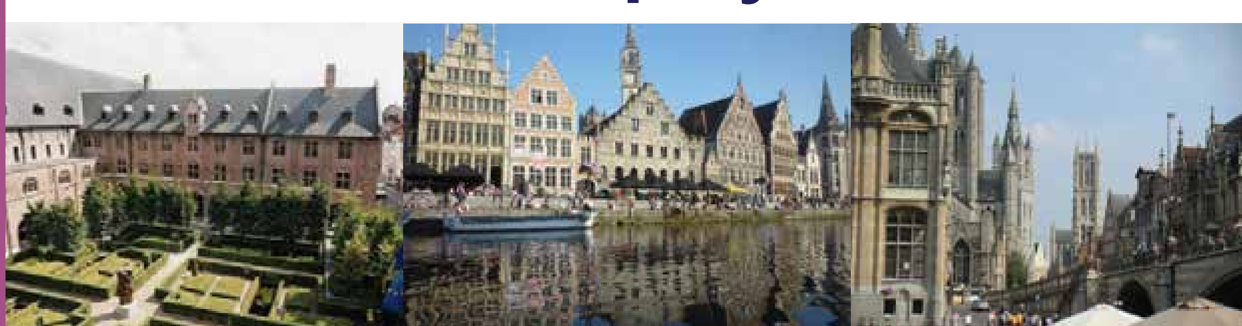
Fast forward to today, as the same force, mobility, is driving the next wave of the display revolution. This is happening in front of our eyes. The advancements in ICs, software, and wireless communications technologies enable us to do practically anything, information-wise and communication-wise, with devices small enough to fit into our pockets. However, as the trend in recent years clearly indicates, we as human beings want to see larger and higher-quality images (does anyone still remember the size and resolution of the display on your first smartphone?). How do you put a large display in a small device? Well, another display form-factor revolution, from rigid to flexible, will do just that.

In this special issue on Flexible and Wearable Technology, we have prepared three excellent articles to report the current status of flexible AMOLED technology, and, equally important, the efforts being made to tackle the first applications that will jump-start the flexible revolution.

A flexible display needs to exist as part of an overall device. Choosing and designing the first device to highlight the benefits of a flexible display is as important as developing the technology. In the first article, titled "Technologies for Flexible AMOLEDs," Dr. Soonkwang Hong and his colleagues at LG Display report their efforts in addressing various technical challenges to successfully bring the world's first flexible OLED display to mass production in 2013, with the G Flex smartphone. Even though the device did not take full advantage of the flexibility of the display, it was a significant milestone for flexible displays and was recognized with an SID Display Application of the Year Gold Award in 2014.

Researchers at ITRI believe that a tri-fold AMOLED display better represents a killer application for flexible displays. As explained in the second article titled, " Foldable AMOLED Development: Progress and Challenges," by Drs. Jing-Yi Yan, Jia-Chong Ho, and Janglin Chen, a tri-fold configuration enables the functionality of a smartphone and a tablet in the same device. In the article, the authors explain in detail the challenges in achieving a folding radius of 5 mm or less and report the successful demonstration of AMOLED displays with folding radii of 5 and 7.5 mm, and in different folding modes, including the tri-fold mode at Touch Taiwan 2014.

(continued on page 36)



Technologies for Flexible AMOLEDs

In 2013, the world's first mass-produced devices based on flexible AMOLED displays entered the marketplace. In this article, the technical barriers and challenges involved in creating the AMOLED panel used in LG Display's G Flex smartphone will be described.

by Soonkwang Hong, Juhnsuk Yoo, Changhoon Jeon, Changheon Kang, Jino Lee, Joungho Ryu, Byungchul Ahn, and Sangdeog Yeo

RECENT YEARS have seen significant research investments in the development of flexible display technology.[1,2] The convergence of many critical components [substrates, barrier layers, electro-optic materials, thin-film transistors (TFTs), and manufacturing processes] is now accelerating the development of flexible displays. Many companies focused on display components are growing up around the flexible-display concept and betting on the paradigm shift to flexible in the future.

This article describes certain aspects of the development of one of the first commercially successful flexible AMOLEDs – the panel used in LG Display's G Flex smartphone. These include flexible substrates, encapsulation techniques, the bonding process, laser-assisted release, lamination, and chamfering.

First, it is helpful to briefly consider the current and future trajectory of flexible-display development. Figure 1 shows a projected flexible-display trend from a curved and somewhat flexible device that takes advantage of the flexible panel within (available now, as with the G Flex) to future devices such as roll-to-roll and foldable displays[3] that offer many potential advantages such as very thin profiles and lightweight and rugged display systems.

Soon-Kwang Hong is currently a Research Fellow at LG Display Co., Ltd., as Head of the PO Product Development Department. His research interests include electrical circuit driving, compensation schemes and structures, and materials and processes related to glass-based and flexible AMOLED displays. He can be reached at skhong@lgdisplay.com.

Flexible Substrates and ELA-TFTs

One of the first requirements for creating a flexible display is a flexible substrate, which can be either plastic or thin glass. Either must be used to replace conventional glass substrates. Figure 2 shows the basic differences between conventional glass-based AMOLED displays and plastic-based AMOLED displays in terms of their vertically stacked structures.

These plastic-based AMOLED displays are composed of a film-based backplate that is a product of an excimer-laser-annealed thin-film transistor (ELA-TFT) on a polyimide (PI) backplane with an inorganic multi-layered buffer and an additional layer of PET underneath. This also includes a face-sealing encapsulation that can protect against moisture and oxygen while providing flexibility. The materials used for encapsulation include a barrier film and polymer layer and are shown in Fig. 4. In sum total, completely different materials, designs, processes, and equipment are required to realize the structure shown at right in Fig. 2.[4]

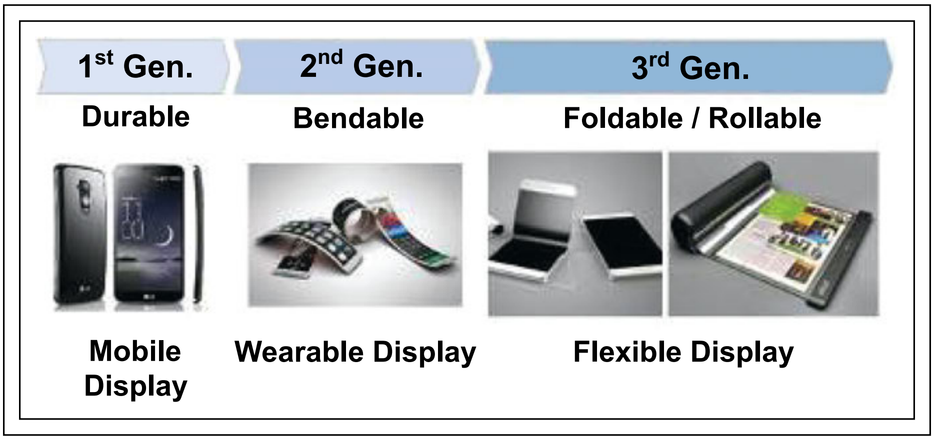


Fig. 1: Flexible displays are now enabling more mobile devices that are more resistant to shock and breakage. These displays are beginning to be used in wearable devices and will in the not-too-distant future enable foldable and rollable devices.

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Research on flexible TFT backplanes has been accompanied by studies on the effects of mechanical deformation on the TFTs.[5-7] By now, the basic experimental and theoretical information required for the manufacture and use of flexible TFT backplanes has been developed. When commencing to develop our flexible AMOLED display, we reviewed with some emphasis TFTs made of low-temperature polysilicon (LTPS) ELA-TFTs for flexible displays on compliant substrates of organic polymers. The developed ELA-TFT on PI shown in Fig. 3 has been implemented with a multi-layered buffer that consists of two different inorganic layers in turn on polyimide organic material.

The realization of this structure requires a PI coating/curing process on the carrier glass, multi-layered deposition, and ELA-TFT fabrication procedures. We developed a new PI material with enough thermal durability (>500°C) for the high-temperature process for TFT fabrication. This material has a different molecular structure that gives it a bonding strength higher than is usual for PI. At the beginning stage of development, the fabricated ELA-TFT on PI had very poor reliability characteristics at a bias and temperature stress (BTS) condition of V_{gs} = 0 V, V_{ds} = –20 V @ 110°C, as shown in Fig. 3. However, we finally achieved excellent reliability from ELA-TFTs on PI by optimizing the multi-layered buffer structure and process conditions as shown at right in Fig. 3.

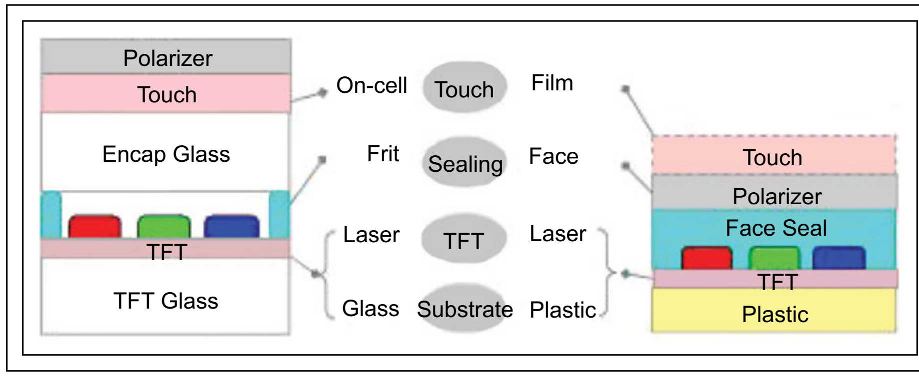

Fig. 2: The structures of a glass OLED display (left) and a plastic-based flexible OLED display (right) show not only that the latter enables a thinner panel, but that the order and composition of the stacks are very different.

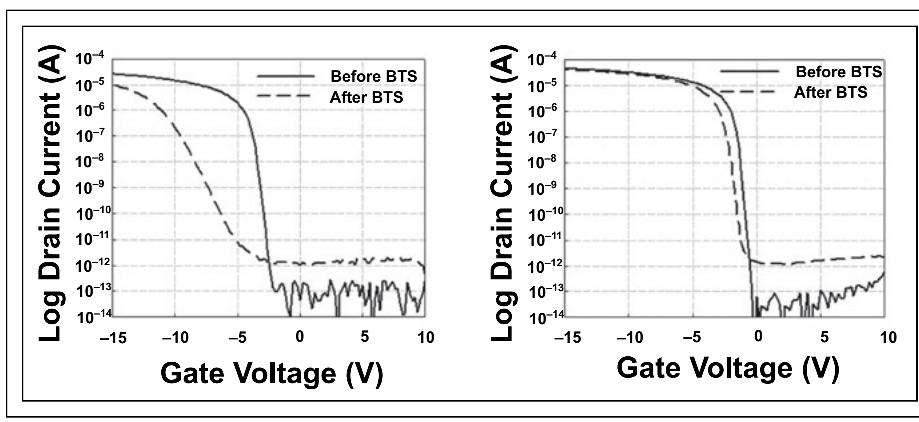

Fig. 3: Performance improvements made to ELA-TFTs on PI are apparent in this comparison of early-stage development (left) to post-optimization (right).

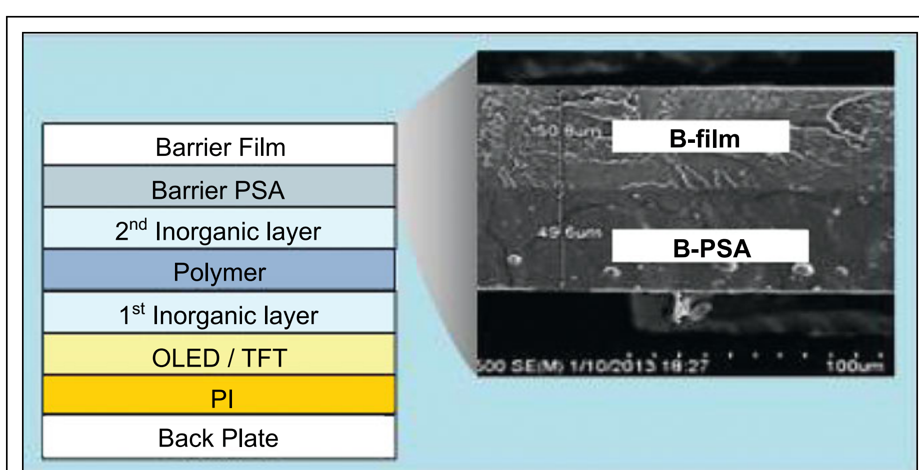

Fig. 4: The face-sealing encapsulation structure is shown at left. The image on the right is a cross-sectional view of the barrier film and barrier pressure-sensitive adhesive (PSA).

Encapsulation

Encapsulation is a key issue in the successful commercialization of OLEDs. Their extreme sensitivity to water-vapor-induced degradation places severe demands on the barrier performance of flexible thin-film coatings. For flexible OLED displays, frit-sealing encapsulation is not an appropriate structure because the OLEDs might be damaged by high temperatures used during the process and the frit-seal material is not intrinsically flexible.

To overcome this issue, we developed a low-temperature flexible encapsulation technology that we were able to use in a thin structure consisting of multi-layered inorganic/organic material. We refer to this as face-sealing encapsulation, with its structure shown in Fig. 4. This structure can be used to achieve a water-vapor transmission rate (WVTR) of ~10^{-6} g/m^2/day, which should suffice for OLED-device reliability. Furthermore, it

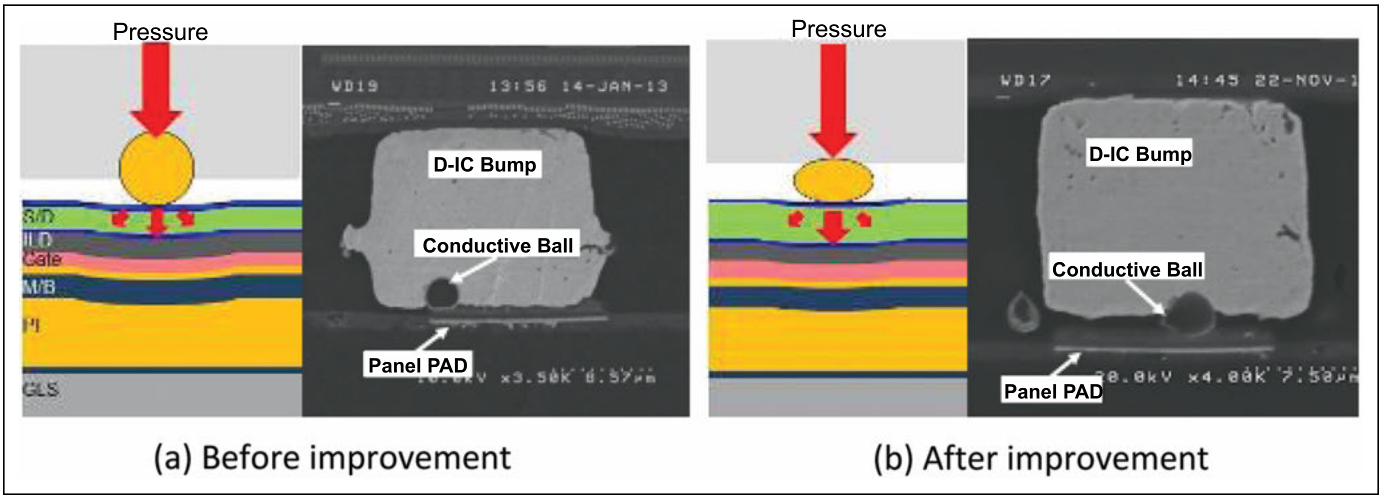

Fig. 5: Researchers improved the chip-on-glass bonding process shown in (a) before improvement by replacing the conductive ball D-IC bump, as shown in (b), after improvement.

enables high-temperature (85°C)/high-humidity (85%) storage reliability for displays. In addition, the newly developed face-sealing encapsulation structure is optically isotropic and has good light-transmission capability.

COG/FOG Bonding Process

We faced many difficulties with regard to the module bonding process. First, the chip-on-glass (COG) bonding process did not work well because the polyimide substrate exhibited high-thermal-expansion characteristics. As a result, we experienced line defects and faulty panels in the early stages of development. To avoid pressure absorption in the PI film (underneath the ELA-TFT layer), we developed a new conductive ball and higher hardness D-IC bump. We also increased the pressure on COG/ FOG (flex-on-glass) bonding as shown in the conceptual images in Fig. 5.

Laser-Assisted Release and Lamination

As is well known, the process temperatures normally used during device fabrication must be much lower when working directly with plastic substrates because the heat resistance of the plastic film is much lower than for conventional glass – usually below 150°C. However, the active elements fabricated at a low temperature tend to have a lower performance than those fabricated at high temperature because high temperature is often essential to achieve a pure and defect-free material. Another difficulty of the direct fabrication process is the dimensional instability of the plastic films because these can easily

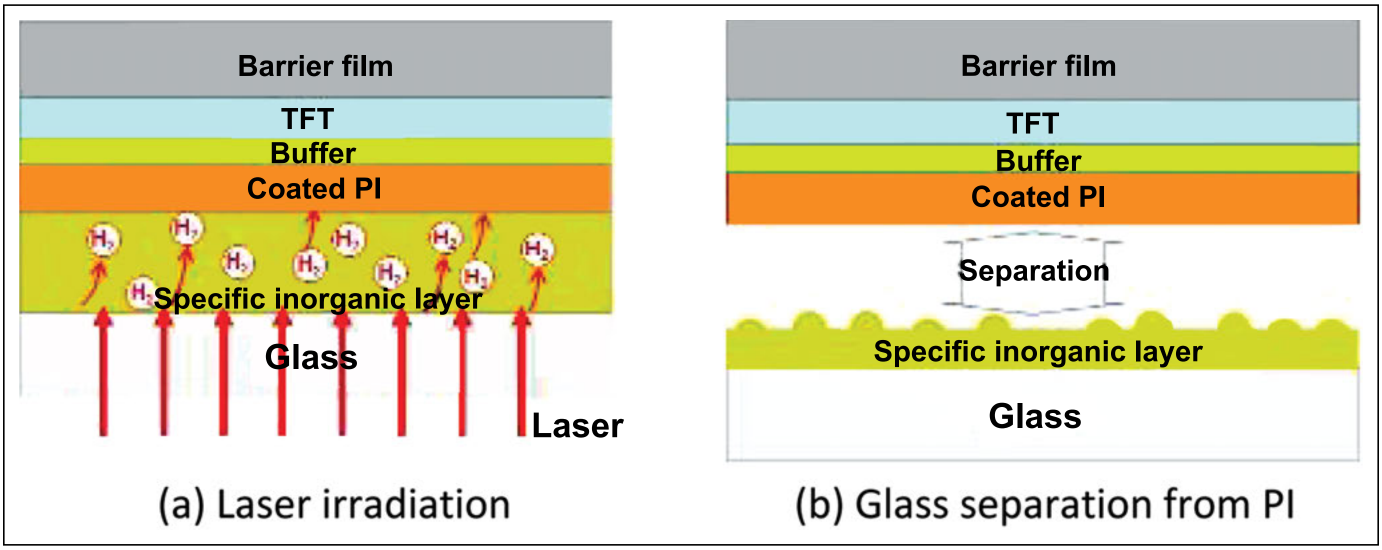

Fig. 6: (a) Laser irradiation occurs on the glass. (b) The PI/TFT layer is then separated from the glass (b).

expand or shrink due to the temperature variation or moisture absorption.

In order to circumvent these difficulties presented by the plastic materials, we developed a transfer process.[8,9] In this method, a high-performance and finely patterned TFT device is fabricated on a quartz or glass substrate using a conventional low-temperature poly-Si TFT (LTPS-TFT) process. Then, the TFT device is lifted off the original glass substrate and attached again to the final plastic film. Therefore, TFT performance as good as that of conventional LTPS-TFTs is expected even on the plastic film unless the TFT characteristics degrade during the transfer process. The transfer process relies particularly on a laser-irradiation technique that is favored for its high process throughput. Figure 6 shows the mechanism of a laser irradiation that lifts off ELA-TFT on PI from the original glass substrate. It uses a specific inorganic layer that plays the role of catalyst to react at the specific wavelength of the laser. When the laser irradiates the inorganic layer, hydrogen gas is released and the inorganic layer releases itself from the ELA-TFT on the PI layer. In summary, this new process allows for the temporary attachment of the PI layer to a glass carrier with a special adhesive layer that can then be deactivated after the TFT forming process using a specific frequency laser. The PI material employed, as mentioned earlier, has several unique properties that allow it to withstand the high temperatures associated with the TFT fabrication process.

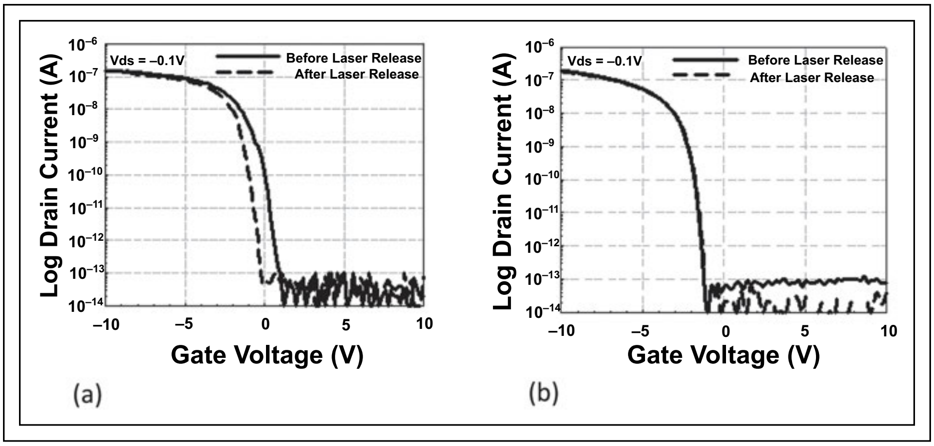

Fig. 7: (a) TFT-on-PI characteristics appear in the early stage and (b) after process optimization.

We could achieve good TFT-on-PI characteristics by optimizing the laser-irradiation process without any performance change after laser irradiation, as shown in Fig. 7.

Panel Corner Chamfering

Flexible OLEDs offer some manufacturing advantages, not just challenges. One of these is the simplicity of processing the panel shape, making it possible to reduce unnecessary areas quite easily. For example, we were able to remove the area that has no patterns in both corners of the pad in the panel through simple chamfering and laser-trimming processes, as shown in Fig. 8(a). In the early stages of development, we did have difficulty with abnormalities caused by cracks in the gate-driver-circuit clock line that is located near the chamfering line. To remove this crack "phenomenon," we redesigned the chamfering lines by removing inorganic layers that were more brittle than others and by optimizing the chamfering process. As a result of this pad corner chamfering, we were able to realize a very narrow pad bezel design in the smart

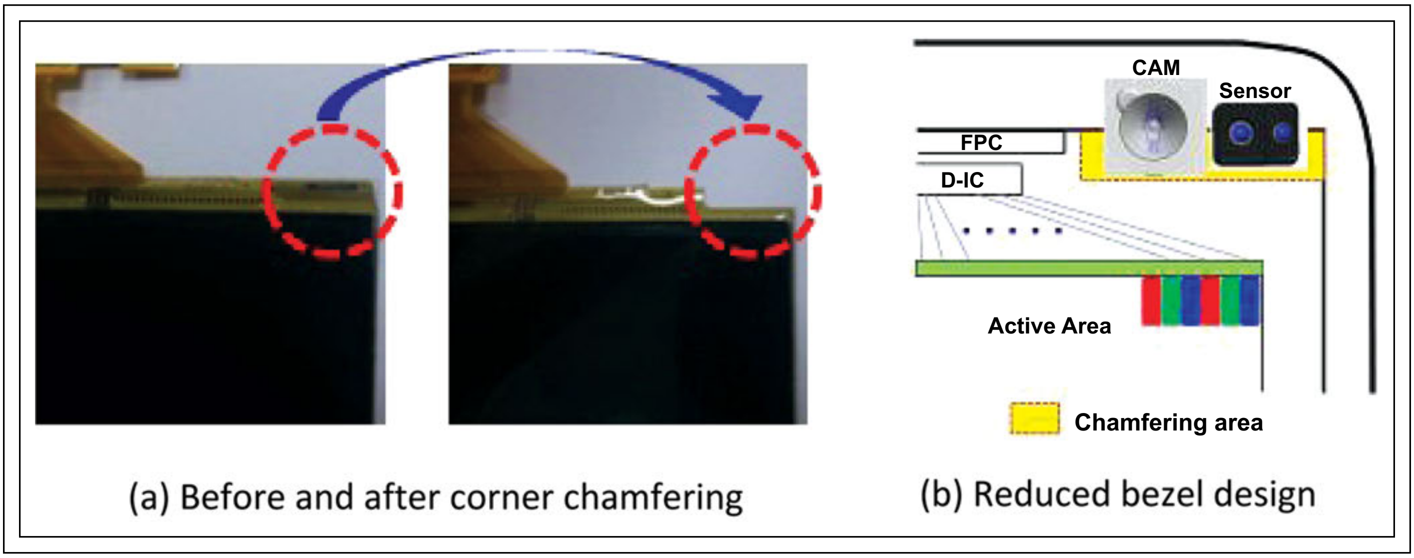

Fig. 8: In (a), the result of chamfering one of the panel corners is displayed. The schematic in (b) shows how it was possible to reduce the bezel size after the chamfering.

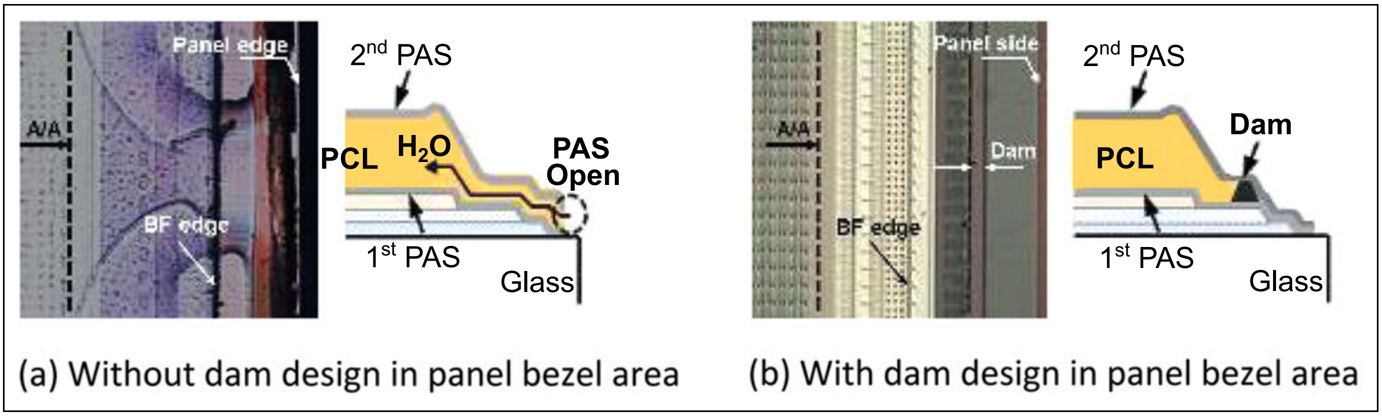

Fig. 9: *A dam was added (b) to the bezel area of the panel in order to prevent PCL overflow (a).*

phone. Figure 8(b) shows the reduced bezel design of the G Flex phone.

Physical and Electrical Reliability Issues

In order to achieve the desired reliability, a new panel design rule was also required. This new approach takes into account the face-sealing encapsulation structure and materials, especially, in the non-emissive area or the bezel. As shown earlier in Fig. 4, the face-sealing encapsulation for the panel consists of three layers: inorganic/organic/inorganic. The organic material is a specific polymer that plays a role in smoothing over height differences due to particle contamination or uneven surface conditions.

It was not easy to prevent particle-cover-layer (PCL) overflow failure from the screen coating process at the end of the bezel region. In this case, the second passivation layer could not cover the entire polymer layer; as a result, water permeation occurred at the area as shown in Fig. 9(a). We added a dam to this area in order to avoid the type of moisture penetration problem shown in Fig. 9(b).

In the early stages of development, we also had difficulty with display abnormalities that stemmed from the integrated gate driver circuit malfunctioning after hundreds of hours of operation at high temperature and high humidity. The root cause was low thermal conductivity of the multi-layered buffer and polyimide that accelerated TFT degradation due to channel self-heating. To achieve electrical reliability, we optimized the circuit design by considering the characteristics of ELA-TFT on PI under thermal and bias-stress conditions. Figure 10(b) shows improved gate driver output waveform under accelerated driving condition.

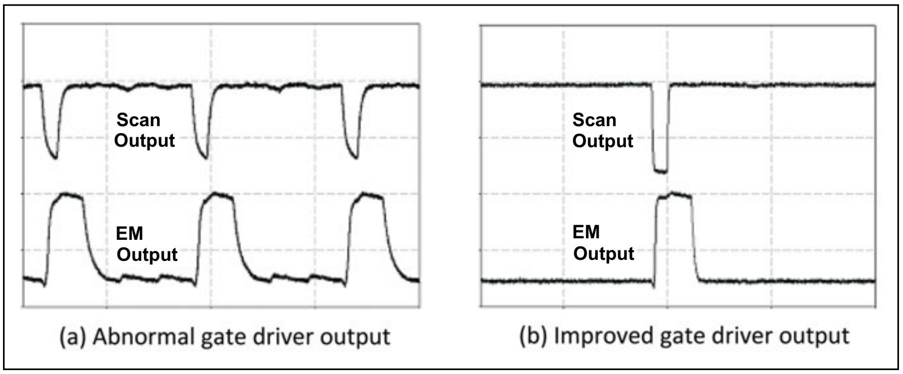

Fig. 10: *(a) The gate driver demonstrated abnormalities under conditions of high temperature and high humidity. At right, (b), it shows improved output as a result of optimized circuit design.*

Successes and Further Challenges for Flexible OLED Displays

Figure 11 shows a flexible display panel and the commercialized smartphone (the G Flex) that was launched on a 5.98-in. flexible OLED manufactured by LG Display. Compared to other flat-panel displays, this panel has very thin, light, and bendable characteristics. Even the smartphone itself has some flexibility.

The processes and materials we developed – ELA-TFT on PI and face-sealing encapsulation with a new panel design, the optimized COG/FOG bonding process, and the laser-induced carrier glass release and back-plate lamination process – enable the efficient mass production of flexible OLED panels that are reliable enough to be used in commercial products. Having been successful in overcoming so many technical barriers and challenges to realize this product, we are confident in the overall future of flexible OLED displays.

The OLED panel shown in Fig. 11 has a bending radius capability of about 15 mm, though when integrated in a smartphone the construction of the device limits that bendability to a certain degree.

With regard to further challenges in flexible-OLED-display design, we are currently focusing on several technologies. First, we need to achieve more flexibility and robustness. For the backplane, new materials for the TFT layer and pattern design optimization are

Fig. 11: LG's 5.98-in. flexible OLED panel (left) appears in its G Flex smartphone (right)

necessary. Also, new materials and face-sealing structures are needed for increased flexibility of encapsulation. We are also considering touch on barrier-film structures and new touch-sensor materials. Film thickness reduction of the polarizer, barrier film, and backplate is also a key challenge. However, we believe that the product designs that can be achieved with flexible OLED displays, such as the foldable and bendable displays discussed earlier in this article, will not only enable emerging smart devices, but trigger an entirely new field of innovations – products and technologies not yet imagined.

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Foldable AMOLED Display Development: Progress and Challenges

Foldable AMOLED displays may represent the first significant application for flexible displays. In order to realize this technology, manufacturers must overcome challenges such as high stress and fatigue in the foldable area. The authors, from Taiwan's Industrial Technology Research Institute (ITRI), propose several approaches to overcoming these challenges and describe demonstrated AMOLED modules having a 5-mm folding radius.

by Jing-Yi Yan, Jia-Chong Ho, and Janglin Chen

THE introduction of cathode-ray tubes (CRTs) changed forever how information is displayed by enabling dynamic rather than static content. This was the first wave of the display revolution. Thin-film-transistor liquid-crystal displays (TFT-LCDs) marked the beginning of the second wave of the display revolution, which enabled the popularity of personal computers (PCs) and, later, mobile phones. Although the TFT-LCD was a great achievement, for portable devices, the current LCD on glass substrate falls short in some important respects. Devices that can fit into a pocket or purse have displays that are too small for many applications. Larger tablet screens increase the weight and fragility of devices that are not as conveniently portable. Consumer-product makers have tried to solve these issues by increasing the display size of the phone or reducing the weight of the tablet. Neither of these approaches is perfect: today, many consumers own or carry both a tablet and a phone, and a challenge exists with regard to seamless information synchronization between devices.

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Flexible Form Factors

Due to the above-mentioned limitations of current mobile devices, there is a need for change in the basic form factor of displays, from rigid to flexible (foldable or even rollable), from heavy to light weight, and from break prone to shatter proof. The concept of flexible displays (the third wave; see Fig. 1) was proposed years ago, and there were actually plastic LCD products, however short-lived, in the marketplace.

In 1998, for example, Sharp announced a product with a twisted-nematic liquid-crystal display (TN-LCD) based on a plastic rather

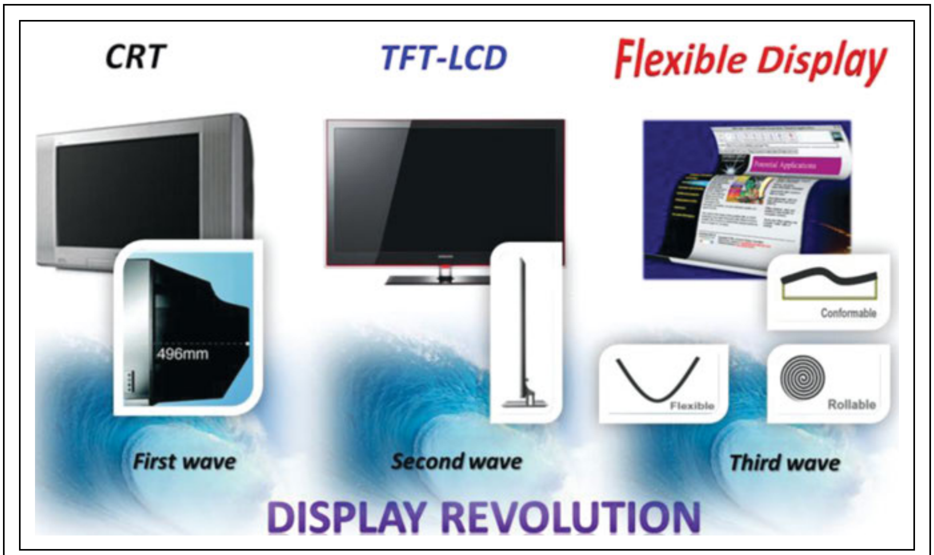


***Fig. 1:** Display revolutions of the past, present, and future are represented as three technology waves, from CRTs at left to flexible displays at right.*

than a glass substrate. The intent of the design was to produce lighter, harder-to-break panels. A number of technical issues are thought to have obstructed that realization. Among these were difficulty in cell-gap control, poor image quality of the LCD on a plastic substrate, and inferior thermo-mechanical properties of plastic relative to glass.

More recently, the two major hurdles for flexible displays have been the lack of a suitable flexible substrate material and the challenge of manufacturing flexible displays with existing TFT processes and equipment. At the Industrial Technology Research Institute (ITRI) in Taiwan, we began addressing the above two issues approximately 10 years ago. The result, our Flexible Universal Plane (FlexUP)[a] technology, proposed and developed in ITRI's Display Technology Center (DTC), won the R&D 100 Award and the *Wall Street Journal*'s Innovation Gold Award in 2010.[1] This technology and similar methods are now widely reported in industry literature and research centers alike.[2,3]

In order to lead off this new or third-wave display revolution, a start-up company, FlexUP Technologies Corp., was spun off from DTC in 2014 to provide the flexible-substrate solution for the display and/or non-display industries such as touch sensors, solar panels, OLED lighting, and digital radiography.

AMOLED Display Advantages

Compared to a TFT-LCD, an AMOLED display is far more attractive for use on flexible substrates. Because it is self-emissive, it does not require the use of a backlight, light-guide plate, or brightness-enhancement film, allowing for a display that is easier to bend, flex, or even fold. Besides this desirable simplicity in structure, an AMOLED display also offers a high video rate, wide color gamut, and low power consumption.

Major display manufacturers such as Samsung and LG Display have formally adopted and disclosed flexible AMOLED displays in their companies' technology and product roadmaps and at the annual SID Symposium held during Display Week.[5,6]

Semiconductor Energy Laboratory Co. (SEL) of Japan also has demonstrated tri-fold and curved flexible high-resolution displays at the Display Week 2014 Symposium and at Display Innovation 2014 held in Yokohama, Japan.[7,8]

Recently, there have been several commercial products based on flexible AMOLED displays introduced into the marketplace. (These products are not bendable or foldable, but take advantage of the flexible AMOLEDs to realize new form factors.) In late 2013, Samsung and LG Display launched curved smartphones, the Galaxy Round and G Flex, respectively, which use a plastic-based AMOLED screen with a radius of curvature greater than 100 mm. (The G Flex device actually does flex repeatedly, in addition to being curved.) Furthermore, toward the end of 2014, both Samsung and Apple announced their latest portable devices based on flexible AMOLED displays, the Galaxy Note Edge and the Apple Watch, respectively. All of these products feature displays with low-temperature polycrystalline-silicon TFT (LTPS-TFT) backplanes.

These consumer products are thus far riding on limited features of flexible AMOLED displays, namely, light weight and curved unbreakable surfaces. They have not offered much value differentiation from conventional glass-based portable devices.

We believe that the tri-fold AMOLED display will better represent a killer app of the third-wave revolution of the flexible display. Figure 2 illustrates scenarios for how the portable tri-fold AMOLED display might work in our daily lives. In the example, there are several application modes for tri-fold devices. The carry mode is with the device closed and folded up, in which it can easily be placed into a pocket or purse. This mode also prevents the display screen from being scratched. Another mode is the smartphone, used for making or receiving calls. The tri-fold device can also be used in tablet mode, with the full screen opened to display the maximum amount of information. Also, as illustrated in Fig. 2, this device can be used in semi-tablet mode for specific applications.

With this design, consumers would only have to carry one portable or foldable device and not have to worry about data synchronization. This flexible display, naturally, would weigh significantly less than a glass-based one because a plastic film is used as the substrate. ITRI's belief is that in order to realize those applications and meet other consumer-product design wishes such as a slim bezel and thinness,[9] the folding radius should be 5 mm or less.

In order to realize the display shown in Fig. 2, many of the existing problems need to be addressed, including the key challenges of reducing stress at the area of folding, selecting

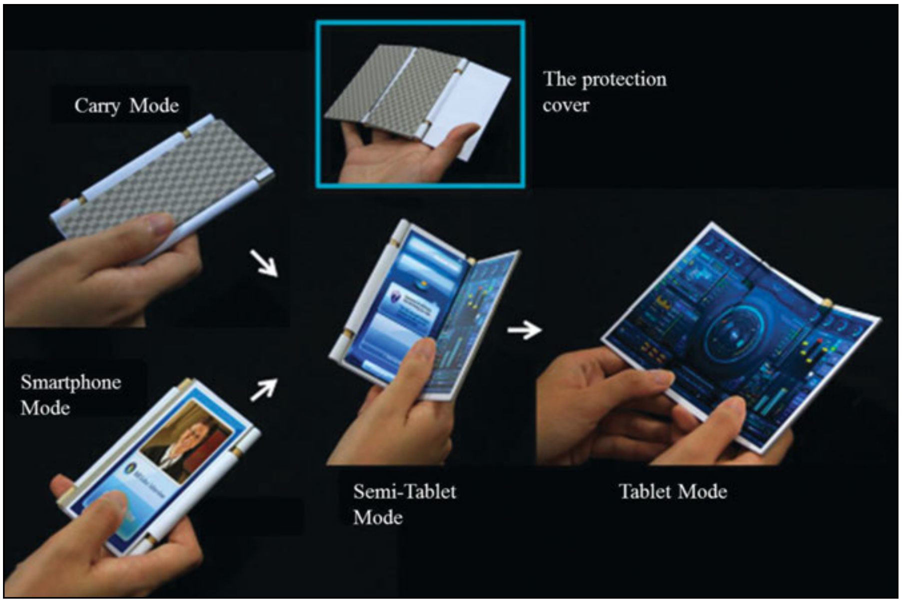


***Fig. 2:** This conceptual design shows modes for a tri-fold display, including, clockwise from upper left, the carry mode, tablet mode, semi-tablet mode, and smartphone mode.*

[a]FlexUP™ is a registered trademark of the Display Technology Center at ITRI.

a proper substrate, determining the ideal stack structure, and optimizing the liftoff process.

Folding Mechanics

In ITRI's laboratory, we ran a simulation of the 2-D stress distribution in the folding area of a flexible AMOLED display with large (50 mm) and small (3 mm) folding radii, respectively, using the mechanical module of ANSYS engineering simulation software. In the simulation, we entered numerical inputs such as layer structure, layer thickness, and the mechanical strength of component materials to calculate the stress distribution. The materials used included typical OLED chemicals as well as common materials for TFT-array processes such as SiO_2 and SiN for the dielectric film; Mo, Ti, Al, Ag, and ITO for the conductive film; silicon for the semiconductor; and polyimide for the substrate.

Based on suggested real-life conditions, we believe foldable displays will need to survive 100,000 fold–unfold cycles without breaking or showing signs of degradation. The rationale for 100,000 cycles is based on a typical consumer's use of 100 cycles a day over 3 years, or 1,000 days.

In Fig. 3, the yellow to blue colors indicate that the stress concentration is lower than the yielding strength, and in the red color region, the stress is near or over the yield strength limit. Figure 3 shows the stress simulation result for different folding radii, and it indicates that there is high stress concentrated in the folding area with the smaller radius (3 mm) and, consequently, the non-elastic deformation will degrade the performance and lifetime of the AMOLED display. This is a huge challenge with foldable display development. DTC is now focusing on proposing and developing solutions to overcome this issue.

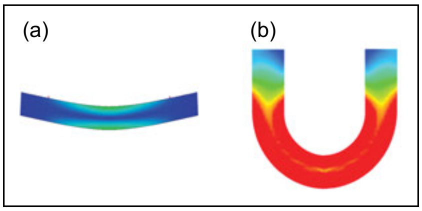


Fig. 3: The mechanical module of ANSYS simulation software was used to show 2-D stress distribution simulation with (a) large (50 mm) and (b) small (3 mm) folding radii, respectively. Yellow and blue indicate that the local stress is lower than the yielding strength, whereas the red color indicates that stress is near or over the yielding strength limit of, in this case, the typical OLED chemicals, common TFT array process materials, and polyimide substrate used in the sample.

Substrate Technology

A highly reliable and robust TFT backplane technology is crucial because OLED displays require a controlled amount of electrical current to be driven through each display element independently to achieve a desired gray-scale illumination. This puts a much greater demand on the performance of the switching devices when compared to those in a typical LCD panel element, which generally require the loading and storage of a predetermined voltage level but no continuous delivery of current to maintain a desired gray level. Any variation in the relative performance of TFTs between display elements on a panel could result in similar visible deficiencies in the displayed image.

Table 1 shows a comparison of existing TFT technology when applied to AMOLED displays. The a-Si and organic TFT technologies fall short, with lower mobility and poor electrical stress reliability. The most promising technologies used to form TFTs suitable for foldable AMOLED displays are LTPS and types of oxides (IGZO, for example). The promised advantages of oxide TFTs include lower manufacturing costs and better uniformity than LTPS. However, the reproducibility of oxide TFTs is currently still a challenge and has for some time kept this technology from being used in mass-market production.[10]

Up until now, there have only been a small number of companies, such as Sharp and LG Display, that are capable of manufacturing IGZO-TFT backplanes for LCDs with limited output. Therefore, until oxide-TFT technology is ready, LTPS-TFTs remain the dominant choice for AMOLED driving.

The major issue with using LTPS-TFTs for foldable displays is the high process temperature required, which limits the choice of plastic substrate. However, the FlexUP technology proposed by DTC addresses this issue. After surveying various material sources, including those originated at ITRI, DTC confirmed that certain specific grades of yellowish polyimide (PI) formulations could provide an ultra-low coefficient of thermal expansion (CTE) – less than 10 ppm/°C – and at a high glass-transition temperature approaching 500°C. The LTPS-TFT process developed at DTC, along with its FlexUP technology and PI material, can be carried out at temperatures up to 450°C.

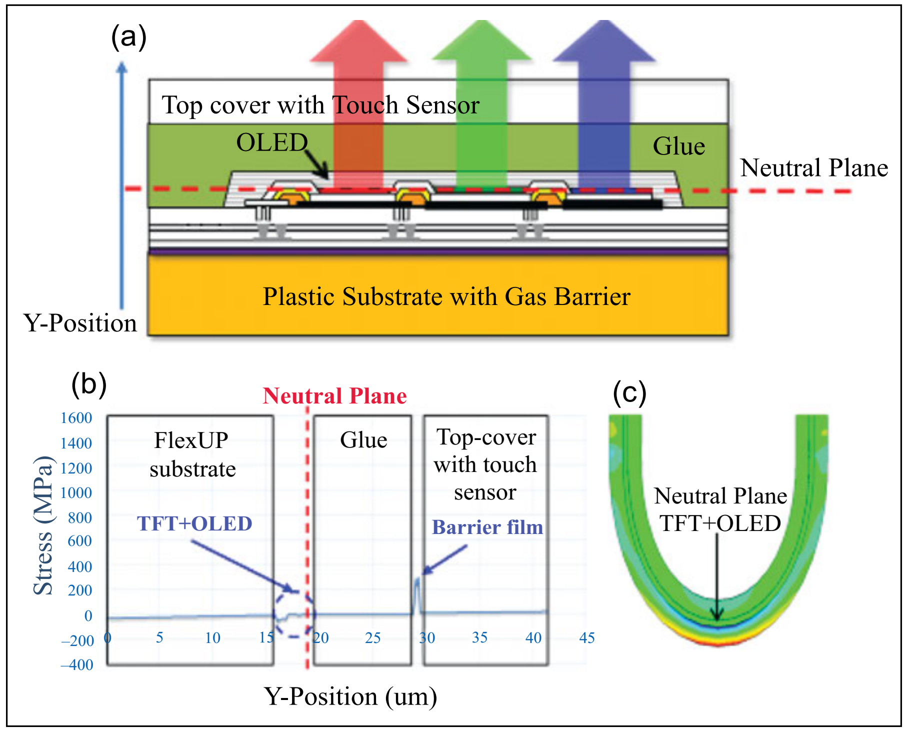
Structural Strategies

As discussed earlier, the high stress concentrated in the folding area is a threat to the lifetime of foldable displays. In view of mechanical stress, the structure of a foldable display can be divided into four parts: the flexible substrate, TFT backplane, OLED, and the top cover film with a touch sensor and glue between the cover and the layers underneath. Figure 3 shows that high-stress contribution in the folding area is a major issue, and DTC has proposed a set of structural design concepts, such as using a softer or stress-absorbing material, and strategically placing the components that are mechanically most vulnerable (TFT backplane and OLED) close to the lowest or zero-stress plane (the neutral plane) to improve the reliability and flexibility of foldable displays.

Table 1: Existing TFT technologies used for AMOLED displays are compared in terms of mobility, reliability, process temperature, and other factors.

TFT technology	a-Si:H TFT	Organic TFT	LTPS TFT	Oxide TFT
Effective Mobility	≦ 1 cm^2/Vs	≦ 2 cm^2/Vs	50–120 cm^2/Vs	5–25 cm^2/Vs
Device Reliability	Poor	Poor	Excellent	Good
Process Temperature	200–380 °C	120–200 °C	<450 °C	150–350 °C
Reproducibility	Excellent	Issue	Excellent	Issue
Slim-border Design	Difficult	R&D	Mature	Available
Cost / Yield	Low / High	TBD / TBD	High / High	Low / TBD

Fig. 4: The structure of a foldable touch AMOLED display appears in (a). In (b), the stress distribution in the perpendicular direction of a foldable display with an optimal structural design is shown. The 2-D stress distribution simulation of a 3-mm folding area with the optimized design appears in (c).



These result in a reduction of the total stress in the TFT backplane. With these parameters optimized, the foldable display structure and 2-D stress distribution simulation with a 3-mm folding radius is shown in Fig. 4. The stress concentration has obviously been reduced in the folding area by using DTC's structural design. The folding area is now working within an elastic deformation regime, and the lifetime and performance are thus improved. In summation, we optimized the structure by placing the neutral plane close to the middle part of the whole panel structure and reducing the total thickness to 60 µm, thereby reducing the film stress of each layer.

We Have Liftoff

Constructing a flexible AMOLED display using the techniques discussed above requires the use of high-temperature processes and extremely accurate control of the flexible substrate material during the fabrication process. This is achieved by using the unique FlexUP process of coating the flexible substrate to a glass carrier with a weak intermediate adhesive layer but with strong edge adhesion. After the fabrication process is complete, the final step is to detach or release the flexible AMOLED panel from the glass carrier without causing any damage to the display.[11]

One of the advantages of FlexUP technology lies in the release of the AMOLED panel by a mechanical de-bonding method.[12] Coupled with the optimal display structural design, the de-bonding process with FlexUP can be carried out at a speed of 100–500 mm/min without causing damage to the flexible AMOLED panel. In order to confirm the performance of the de-bonding method, we tested the flexible AMOLED panel by illuminating it before de-bonding; kept the power on during the de-bonding process; and took photos at the beginning, middle, and end of the de-bonding process. Also, we carefully examined the flexible AMOLED display image before and after the de-bonding process. The result is shown in Fig. 5. There is no line or point defect, nor mura generation, in the flexible AMOLED panel following the de-

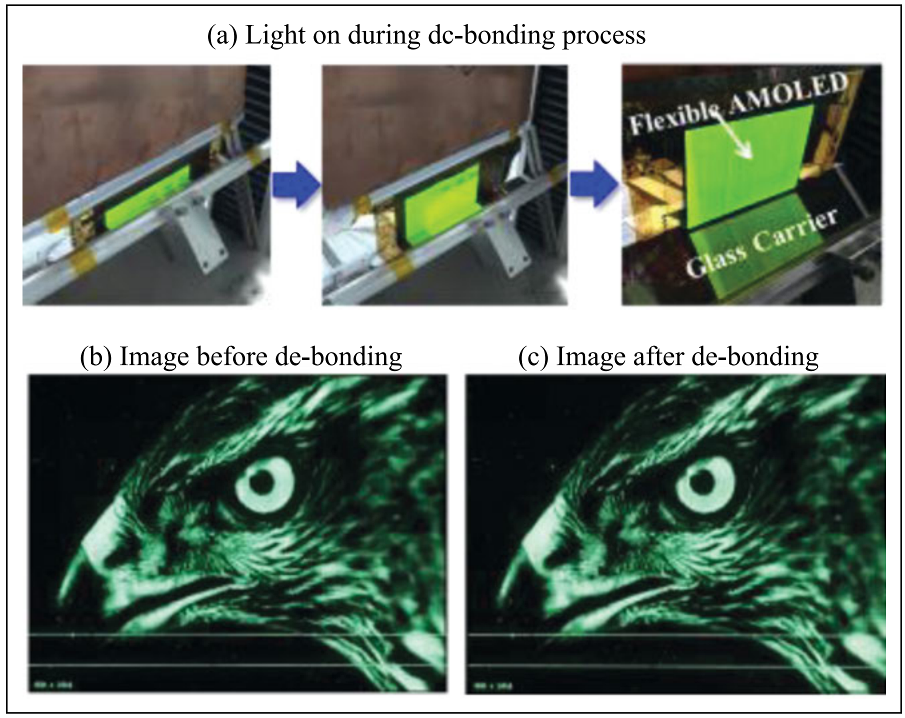


Fig. 5: (a) The flexible AMOLED display is illuminated during the de-bonding process, and the flexible AMOLED image is shown (a) before and (b) after the de-bonding process.

bonding. Therefore, the FlexUP technology combined with the mechanical de-bonding method represents a fast and robust process for foldable AMOLED display manufacturing.

The Foldable-AMOLED-Display Demonstration

DTC successfully demonstrated several types of foldable AMOLED display modules at the Touch Taiwan 2014 Exhibition. These were AMOLED displays with folding radii of 5 and 7.5 mm, and in different folding modes including the display bent inward, outward, and in tri-fold mode. All of these foldable displays, made with the methods shown in Fig. 4 and the liftoff process described above, continued to work after thousands of foldings and unfoldings without showing any sign of image-quality degradation. Figure 6 shows the foldable AMOLED modules shown at the International Touch Panel and Optical Film Exhibition 2014. In the future, DTC will continue to challenge the limits of foldable AMOLED displays with a folding radii of 3 mm and less.

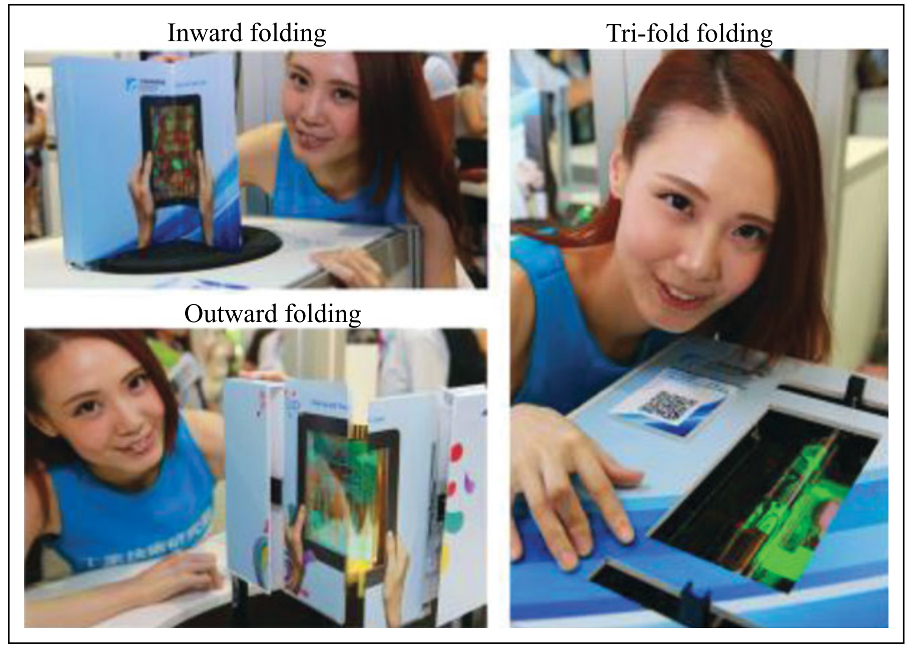


Fig. 6: This demonstration of three modes of foldable display – inward, outward, and tri-fold – appeared at the International Touch Panel and Optical Film Exhibition 2014 in Taiwan. The folding radius is from 5 to 7.5 mm.

Frontiers in Foldability

After years of development, the foldable AMOLED display could represent a truly killer app for flexible displays in the consumer market. The new form factor injects a much-needed freedom in design for mobile as well as wearable display products. Although panel makers should be able to quickly scale the technology as soon as capital investment for the facilities is in place, technical challenges, such as those described in this article, still exist. These challenges should present excellent opportunities for innovation-minded scientists and engineers.

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A World of Wearables

The ever-evolving category of wearables includes items that range from essential to whimsical.

by Jenny Donelan

"IT's hard to miss the topic of wearable electronics lately," wrote guest-editor Xiao-Yang Huang in our May/June 2014 issue. Six months later, it's still true: wearables are everywhere. If you do not use a fitness tracker, such as Fitbit or Jawbone, you probably know someone who does. Apple's smart watch, due out around the time that this issue is released, has been much in the news and is both widely derided and widely anticipated, even though it is hardly the first such device on the market. And even if Google glass has failed to win the public's affection, everyone knows what it is. It has already spawned add-ons and imitators, as discussed in this article. In addition, there are some fairly to really "out there" wearable concepts, including a motorcycle helmet with GPS, camera, and Bluetooth connectivity; a device that clips onto a garment near your collarbone and vibrates to warn you when you are slouching; and a dress that telegraphs your inner emotions using blue LEDs.

The following roundup provides just a sampling of the wearables that are out there. They keep coming – and that's a good thing for consumer electronics in general and the display industry in particular.

Tracking Fitness

The most successful category of wearables to date – the fitness tracker – is the one with the least emphasis on displays. Some – Jawbone's UP line, for example – do not even have displays, relying completely on syncing to your device of choice. It would be good news for the display industry if fitness trackers did incorporate more displays because fitness trackers will almost triple by 2018, compared to an estimated 19 million in use in 2014, according to a new report by Juniper Research. Juniper is projecting that fitness devices will remain the dominant wearables segment until 2018.[1] One in ten U.S. consumers over the age of 18 now owns an activity tracker from Jawbone, Fitbit, Nike, Misfit Wearables, and others, according to another recent wearables report, from Endeavour Partners.[2] Not all is rosy, however, the Endeavour report continues. The devices, while fascinating to their owners when new, often fail to sustain interest. According to Endeavour, more than half of U.S. consumers who have owned an activity tracker no longer use it. A third of U.S. consumers who have owned one stopped using the device within 6 months of receiving it.

Until recently, the three most popular fitness trackers were the Fitbit, the Jawbone, and the Nike Fuelband. The Fuelband, introduced in 2012, enjoyed initial success. but it is reported from numerous sources that even though the device is still for sale, Nike has dismantled its Fuelband development team.

According to a CNET report from last May, the Fitbit represented 50% of the world's wearable market. [3] The Fitbit uses a three-dimensional accelerometer to sense user movement and employs a simple OLED display to provide information such as the battery level. Most recently, these simple trackers have evolved in the direction of a smart watch, as in the not yet released Surge shown at far right in Fig. 1.

Fig. 1: Fitbit's fitness tracker lineup includes, from left to right, the Zip; the One (with sleep tracking); the Flex, which uses LED lights to show you how close you are to your goals; the Charge, with caller-ID and sleep tracking; a WiFi smartscale that syncs with trackers; and the soon-to-be-released Charge HR with heart-rate tracking and Fitbit Surge Fitness Super Watch with GPS and numerous other features. Image courtesy Fitbit.

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Jawbone's UP and other tracking products are high style, including its recently released Move tracking device, shown in Fig. 2. The UP has no display whatsoever. The Move has a simple LED display that appears on the flower-type button when pressed.

Google Glass and More

Google made, and continues to make, headlines with its head-mounted hands-free smartphone technology. As clever as it is, however, people just do not seem to want to wear it – or be seen wearing it. It is very uncommon these days, in any major U.S. city, to see people sporting the devices in public. This is not for want of trying on Google's part. One of its latest efforts is the Made for Glass line co-created with fashion designer Diane von Furstenberg (Fig. 3). It seems more likely, as posited by analyst Paul Gray in this issue's Display Marketplace on wearables, that the hands-free augmented-reality possibilities of the technology will find better use in industrial and health-related applications. For a novel look at how Google Glass can be used to help individuals with vision impairment, see the article, "Augmented Edge Enhancement on Google Glass for Vision-Impaired Users," in the 2014 May/June issue.

A sign that the Google Glass concept may have life in it yet is that other manufacturers have seen fit to copy or make products that work with it. Rochester Optical is collaborating with Hong Kong eyewear designer Simon Chim to develop a range of frames called chimmm that are designed specifically for smart glasses, including Google Glass. And, as reported in this month's regional business article on Japan, Toshiba just came out with a Google Glass type of technology that is lighter than Google Glass. "Toshiba Glass" won an innovation award at CEATEC Japan last year.

Smart Watches

There are a number of products in the smartwatch category – the Moto 360 from Motorola, LG's G Watch R, Samsung's Gear 2 Neo, and more. While the soon-to-be released Apple Watch (Fig. 4) is probably the most talked about, this category has been in existence for several years. In fact, it could be argued that sportwatches and heart-rate monitors were simply early smartwatches.

Many experts cite the no-frills Pebble, with its basic streamlined looks and intelligent apps, as a successful realization of the concept. The Pebble Steel received the highest praise for a smart watch in CNET's recent "Best Wearable Tech of 2014 Awards."[4] These watches feature a low-reflectivity LCD with a backlight that looks a lot like e-Paper (Fig. 5).

Fig. 2: *Jawbone's new UP Move tracker is a high-style budget-priced ($50) entry-level tracker with a simple LED display that lights up in the center button when activated. Image courtesy Jawbone.*

Fig. 3: *The Made for Glass line, co-designed with Diane von Furstenberg, is as high-fashion as Google Glass is likely to get. Image courtesy Google.*

Fig. 4: The Apple Watch is both eagerly awaited and preemptively derided. Its looks are not especially fashion-forward, so the success of the device will depend on its operation and its apps. Image courtesy Apple.

The smart watch or "smartband" category has attracted a number of fashion-minded folks. The Klatz watch, a prototype still in the fundraising stage (you can check it out on Indiegogo), has a simple LED screen, but doubles as a handset and without question makes a fashion statement (Fig. 6).

Another high-fashion entry is the i.amPULS smart band recently introduced by musician and entrepreneur will.i.am. According to the literature, the PULS wearable is untethered and has the ability to make/receive calls while operating independently of any smartphone – it does not require Bluetooth or close proximity to a smartphone.

Unclassifiable Wearables

There is a huge variety of wearables that cannot be classified into the above groups, like the aforementioned anti-slouch monitor (the Lumo Lift) and the motorcycle helmet (the Skully). One subcategory seems to be wearable devices, especially clothing, that telegraph our moods, including whether we are attracted to another person. The advisability of this on a daily basis is debatable. Nevertheless, it's an interesting concept and might work on the dance floor with a group of 20-somethings.

Fig. 5: The Pebble watch, launched through Kickstarter, is one of the more successful smart-watch designs, popular with the public and press alike. Image courtesy Pebble.

Fig. 6: The company behind the Klatz watch, with an LED readout, is still in the fundraising stage. Image courtesy Klatz.

Synapse is a digitally designed and 3-D-printed interactive dress (really a bodice and headset) that runs on Intel's Edison micro-controller and is printed in a flexible material called TPU 92A-1 by the Belgian company Materialise. The dress was designed by fashion designer Anouk Wipprecht, who has created other pieces of electronic clothing (Fig. 7).[5]

There are thousands more wearables than were mentioned here, and more being developed every day. The vast majority of products will never make it to commercial distribution, but a great few will cross the line from becoming something we want to something we think we need. The smartphone has become that device for many of us. The next wearable superstar will have to incorporate great functionality, style, and portability that makes sense beyond the novel.

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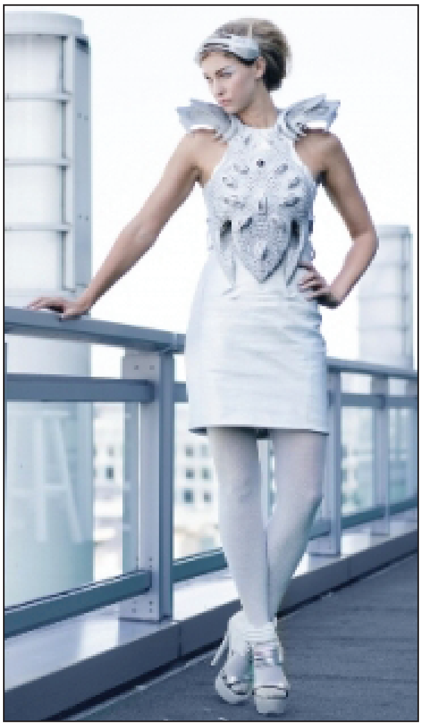

Fig. 7: This space-age-looking outfit monitors brain signals through a headpiece that, in turn, illuminates the leaf-shaped designs on the bodice in varying intensities of blue, depending on mood. Source: Intel-Edison based Synapse dress, photographed by Jason Perry.

[3]http://www.cnet.com/news/fitbit-rules-50-percent-of-the-worlds-wearable-market/
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Unlock the Full Potential of Wearables with Organic TFTs

OTFTs brings unique benefits to both product function and display manufacturing and is a key to unlocking the potential utility of wearables.

by Paul Cain

THE pace at which wearable electronics is evolving is now faster than ever before. In the last couple of years, "wearables" has become a recognized term in its own right. It refers to an increasing list of applications, including smart watches and smart bands, smart headgear and glasses, and now even smart jewelry and smart clothing.[1]

Wearable electronics is by no means a new market – we have been wearing items such as headphones, hearing aids, and digital watches for decades. However, most people now consider wearables to be those applications with electronics connected to the outside world – *i.e.*, where they form part of the "Internet of Things." In many cases (as in exercise monitors, for example), the wearable device is the bridge between the human body and the wider world. This intimate monitoring and interaction are much of what is driving excitement and opportunity in this market. In terms of technologies, low-power wireless communications and increasingly integrated MEMS packages have been key in achieving market success thus far.

Wearable electronics offers a huge amount of utility options to users – and the industry is presently in a phase of adapting and learning what end users really value. Undoubtedly, many of the innovations will be the output of agile and creative hardware startups with the vision and energy to bring something new to customers. We have already seen a wave of acquisitions of hardware companies in this area – Intel's acquisition of health-tracking smart-watch company Basis for $100M, Facebook's acquisition of Oculus VR for $2M, and Google's acquisition of WIMM Labs (price unavailable), for example.

New hardware and device technology innovations are a key part of creating wearable product offerings that achieve mass consumer adoption. However, in order for wearable devices to achieve long-term engagement with

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***Fig. 1:** Flexible-display product concepts like this wrist phone show how new levels of utility might be unlocked for smart watches and other wearable devices.*

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consumers, wearable devices must be compelling enough to bring about long-term behavioral change.[2] Plastic electronics will play a key role in providing compelling and unique functionality that unlocks the full potential in this new market.

As an example, a key challenge for many applications of wearable electronics is battery life, particularly for smart bracelets and smart bands, where there is little space for inclusion of a battery. One of the factors driving the use of plastic displays in smart bracelets, for example, is that their thinness leaves room for more battery capacity in a given form factor. Nevertheless, smart watches currently need charging after several days at best. Users have deeply ingrained behaviors and expectations when it comes to watches and power consumption, and these must be overcome if smart watches are to achieve mass adoption with sustained and long-term use.

When personal timepieces first became widely available (in the form of pocket watches in the sixteenth century), users adapted their behavior in order to wind their watches on a daily basis. The benefit of having, for the first time, an accurate measure of time on your person more than outweighed the need to wind the watch every day.

While modern digital watches can operate for years on a single battery, most smart watches last for a few days at best between charging. Improvements in battery capacity are, of course, a solution to this, and there are many companies working on higher capacity and even flexible batteries. There will be huge rewards for those that succeed. However, there is a second effective solution to this that should not be overlooked: Find a way to add enough utility to a smart watch to justify the sustained behavioral change needed to charge your watch on a daily basis. Mobile devices have become ubiquitous despite their battery life; indeed, many of us complain about the life of our phone battery even while upgrading to a new phone with the same (or sometimes worse) battery life. People are prepared to change their behavior to use a device if it can bring them sufficient utility, and new hardware technologies play a big part in increasing the utility of wearable electronics.

It may sound obvious, but if you want to comfortably get a mobile-phone screen's worth of information onto a smart bracelet display, you must have either a flexible or a conformed curved display. Flexible displays can double or triple the amount of information that can be shown comfortably on your wrist – enabling you to do a lot more than is feasible with a planar display (Fig. 1).

Furthermore, interfacing electronics with humans presents its own specific challenges: adopting a one-size-fits-all approach for wearables is often not feasible when rigid components are involved; in particular, for those aspects of functionality that require continuous and intimate contact with the body (sensors that measure vital statistics for example). Similarly, wraparound displays in smart bracelets need to have an adjustable curvature in order to fit a range of wrist sizes.

It is no longer only about front-of-screen performance and power, but also and equally about ruggedness, flexibility, and conformability. These additional dimensions of performance offer industrial designers a entirely new playing field, and it will be a process of convergence to find the optimal use case for flexible OLED displays within the full performance envelope.

The OTFT Advantage

Recently, Plastic Logic has shown flexible active-matrix organic light-emitting-diode (AMOLED) displays made using organic thin-film-transistor (OTFT) backplanes, combined with an OLED frontplane material.[3] This display (Fig. 2) was made using prototyping equipment, and thus contains some defects due to manual handling and cleanroom quality, but the toolkit of processes used to make the TFT array has already been proven to have a high yield, in a real manufacturing environment, for the production of flexible e-Paper displays.

These organic transistors are fabricated using solution-processed polymers (plastics) for semiconductor and dielectric layers in the stack and deposited through a combination of conventional printing and patterning techniques at low temperature, using standard flat-panel-display (FPD) equipment with low-temperature processing. A schematic cross section of the flexible array stack for a top-emission architecture is shown in Fig. 3, including flexible organic layers for semiconductors and dielectrics. The low-temperature process enables the stack to be fabricated directly onto a third-party barrier substrate material, thereby simplifying the stack and process. Further technical details can be found in the *2014 SID Symposium Digest* paper, "Flexible AMOLED Display Driven by Organic TFTs on a Plastic Substrate."[4]

Such a demonstration would not have been possible 10 years ago because OTFT performance, in terms of mobility, stability, and uniformity, was not sufficient at the time. Since then, the mobility performance level of

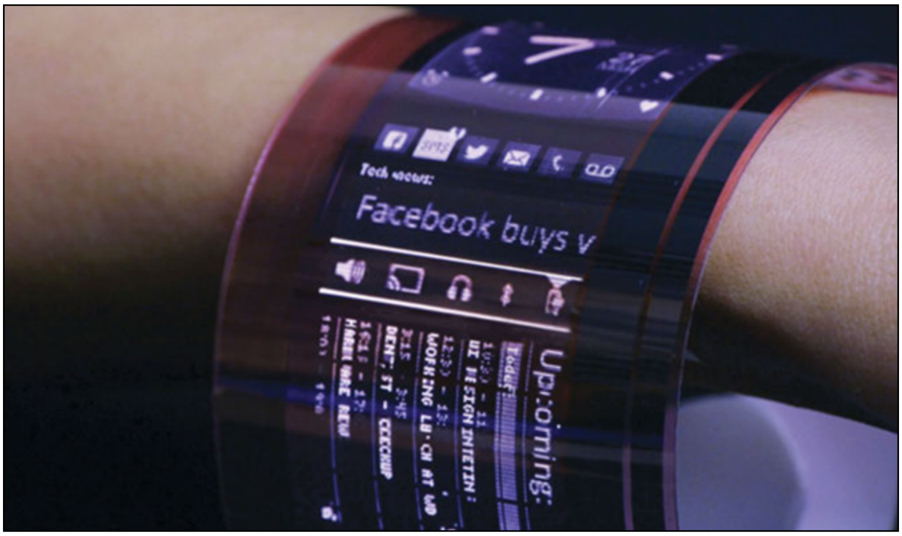

Fig. 2: *This demonstration of a wrist-wrappable flexible OLED display was made using an OTFT backplane printed on plastic.*

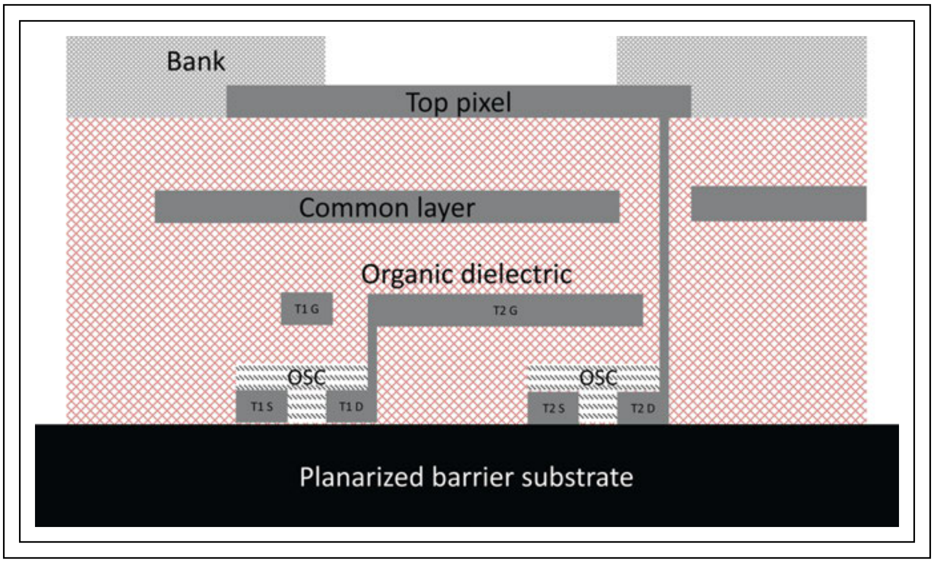

Fig. 3: A schematic stack for the organic transistor array includes plastic (organic) semiconductors and dielectric layers and direct integration of the stack onto an integrated barrier substrate (directly enabled by the low-temperature process).

OTFT has risen by several orders of magnitude, to the point where the technology can now be used to drive OLED displays. And materials keep improving so that today's organic materials are now very stable and show excellent uniformity across large areas. This progress has been driven by both improvements in materials sets and novel TFT architectures that increase current density for a given material set. Several materials suppliers have mobility roadmaps to 10 cm^2/V-sec or more in the near future.

The materials stack used in the array is a combination of plastic/organic semiconductor and dielectric layers, combined with thin metal-alloy layers. A key differentiating benefit of OTFT arrays over other technologies that have been developed on glass is the innate flexibility of organic-based materials. At Display Week 2014, we showed that a TFT array can be curved at a radius of around 250 µm (*i.e.*, a matchstick) with no change in transistor performance (Fig. 4).

All of the component materials are naturally flexible; therefore, the overall flexibility of the devices will continue to improve as interfaces are optimized, enabling tighter bend radii and even foldable form factors. Other TFT technologies have one or more inorganic/ceramic layers within their stack, which fundamentally limits the flexibility because of cracking. In contrast, the crack onset strain for organic electronic materials tends to be several orders of magnitude higher than for their inorganic counterparts.

Technologists continue to develop strategies to fabricate ceramic-based TFTs on plastic films because of the prevalent use of these in today's glass-based devices. For example, one way to increase the flexibility of a ceramic-based TFT on plastic is to position the most fragile layer at the neutral axis of a stack of layers. In this way, when the device is curved, there is no strain for that layer (*i.e.*, the one close to the middle of the stack) if the stack contains layers of materials of similar Young's modulus. However, this is a significant design constraint on the final product, and, of course, not all of the fragile layers can be placed at the neutral axis.

In a truly flexible AMOLED display, it is not only the array that needs to be flexible, but the entire display stack, including the encapsulation layers. There are several companies developing increasingly flexible barrier films and barrier processes to allow a tighter radius of curvature. Figure 5 shows an example of an AMOLED-display prototype using an OTFT array, wrapped around a pencil during operation – equivalent to a radius of curvature of approximately 3 mm.

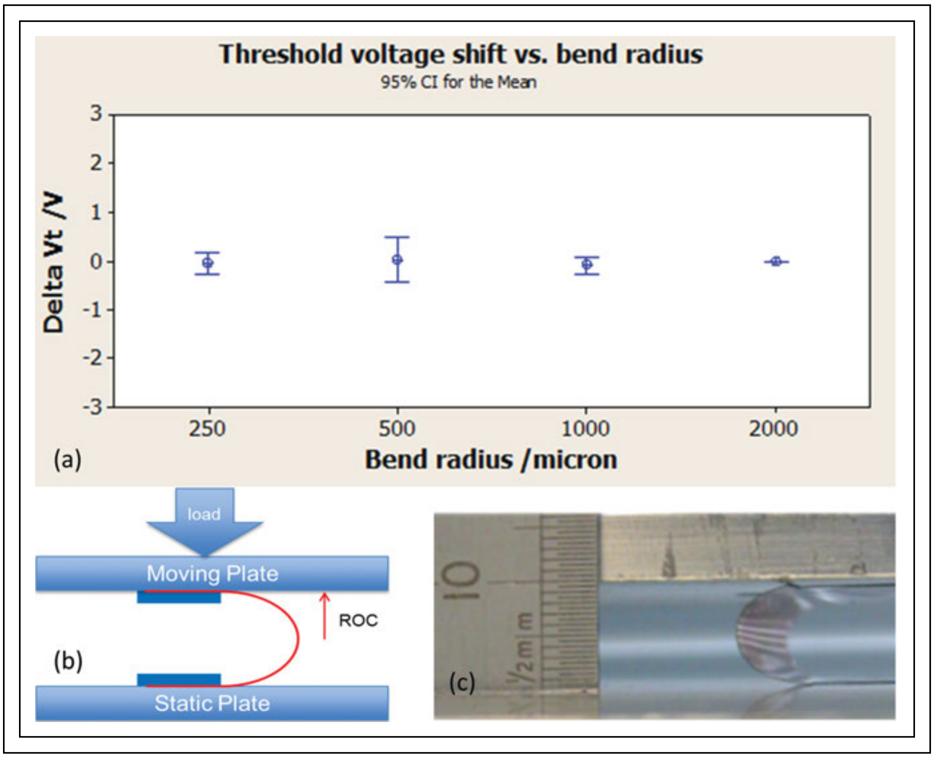

Fig. 4: The OTFT-array electrical performance is unaffected during bend tests down to a radius of 250 µm.

This display was made by using a PET-based barrier film directly as the substrate material – something that is only possible because of the low-temperature nature of the complete organic-transistor manufacturing process – in addition to OLED frontplane materials that were applied by evaporation.

Manufacturing Options for OTFTs

Flexible displays offer benefits not only to product designers and end users but also to display makers. They represent an opportunity for makers to sell more display area not only because these displays will accelerate the development of new markets, but also because more display area (in some cases 2–3 times the area) can be added to a given device because the display can be curved.

The manufacturing process used for OTFT arrays has some significant and proven benefits for display makers as well. Plastic Logic has industrialized a complete toolkit of processes to manufacture flexible TFT arrays for displays and sensors. This array process

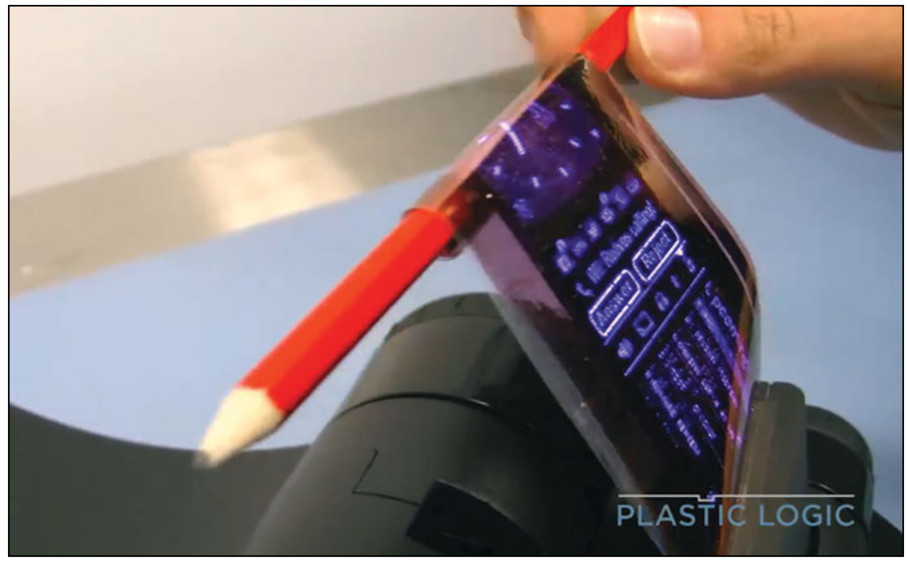

Fig. 5: This flexible OLED display can be wrapped around a pencil while continuing to operate.

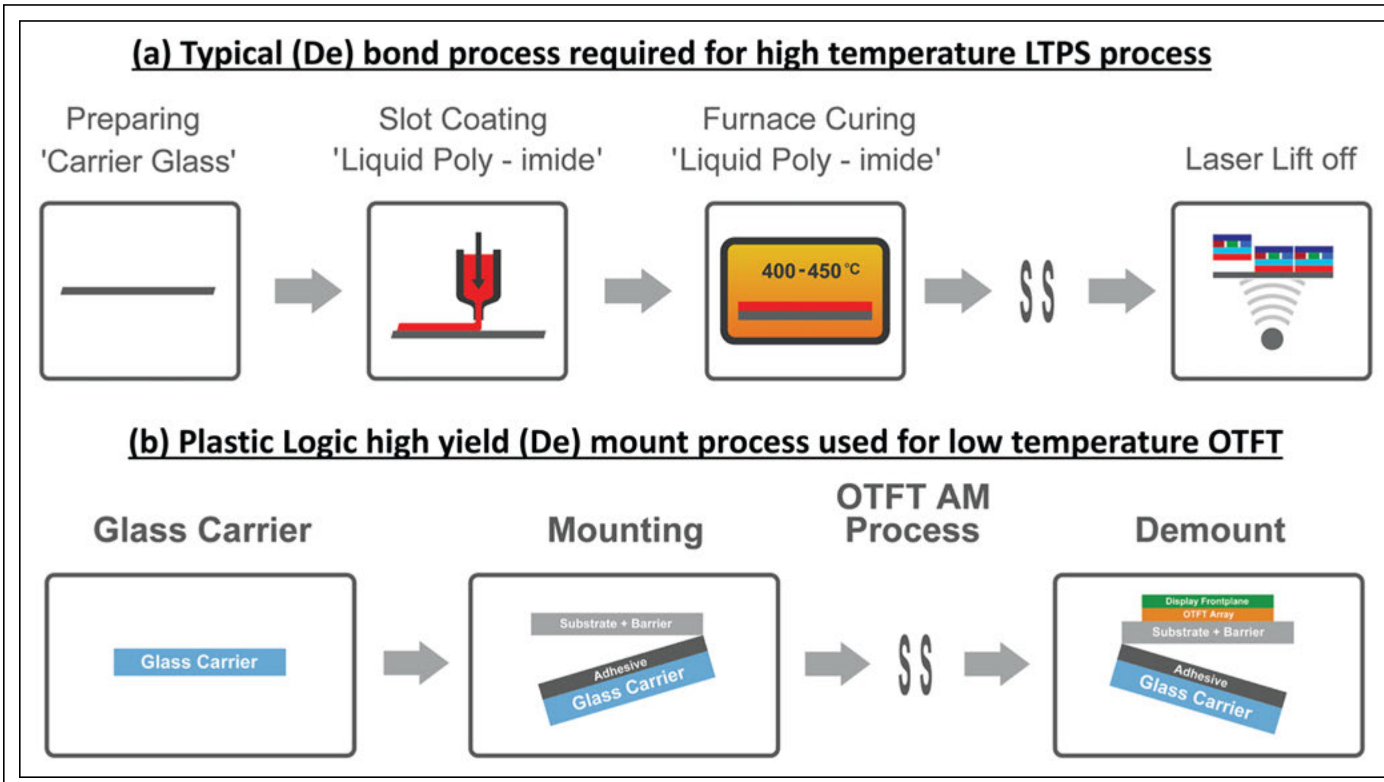

Fig. 6: (a) Processing LTPS arrays on a flexible substrate typically involves the addition of polyimide coating, high-temperature curing, and laser lift-off process steps, which is complex and has yield challenges. (b) By contrast, a simple high-yield mount-demount process was used for OTFTs and is enabled by the low-temperature process for OTFT-array processing.

enables existing display makers to bring true flexibility to the display technology. The process is realized by using organic semiconductor and dielectric polymer solutions as well as a combination of standard FPD printing/coating and patterning methods using equipment that can commonly be found in any LCD line, albeit running different processes.

From a manufacturing perspective, a key benefit of OTFTs for flexible-display production is processing temperature. The maximum process temperature used during the manufacture of our backplane is < 100°C, and this has several distinct benefits for processing transistors on plastic:

- Lower temperatures (< 100°C) mean almost any plastic substrate can be used, including lower-cost plastic substrates such as PET.
- Low temperature avoids thermal effects on the plastic, such as pitch variation in sheet-to-sheet processing (and provides a route to roll-to-roll).
- By avoiding the need for any high-temperature steps during the array process, handling of the plastic substrate is almost trivially simple (using a mount-demount process) compared to alternative approaches.

The third point, substrate handling, is particularly critical since it has such a significant effect on yield. For sheet-to-sheet processing of flexible backplanes, all approaches to handling the plastic substrate rely on somehow fixing the plastic layer to a piece of display mother glass (flat, inert, and compatible with standard FPD handling equipment), and then removing the plastic from the mother glass at the end of the fabrication process. There are radically different approaches that can be taken to achieve this, dictated by process temperature.

For example, one approach to handling plastic substrates is Electronics on Plastic by Laser Release (EPLaR) – a bond/de-bond approach in which a polyimide solution is coated onto a glass carrier and then cured at very high temperature (400–450°C). A variant of the TFT process is then performed (LTPS, oxide, or a:Si), and then the processed plastic substrate is removed from the mother glass at the end of the process by laser release. Such an approach allows the higher-temperature processes needed for inorganic TFTs to be carried out on a plastic substrate. However, the process itself is complex, requires custom equipment and processes, and can only be used with higher cost plastics that tolerate the very high temperatures. Crucially, the debond process (using a laser) occurs at the end of the process flow and thus its effect on the yielded bill-of-material cost is dramatic.

TFT ARRAY TECHNOLOGY	a:Si	LTPS	Oxide	Organic
True Flexibility & Route to Stretch-ability	✘	✘	✘	✔✔
Low Process Temperature	✔	✘	✔	✔✔
Compatible with Roll-to-Roll	✘	✘	✘	✔✔
Mobility	✘	✔✔	✔	✔
Uncompensated Uniformity	✔✔	✘	✔	✔✔
Bias Stress Stability	✘	✔✔	✔	✔
Low Cost of Ownership	✔✔	✘	✔	✔✔

***Fig. 7:** OTFTs have a uniquely enabling capability set for flexible AMOLED displays that can be used for wearable electronics.*

In contrast, for OTFT-array processing on plastic, a simple mount/demount process is employed in which a plastic substrate (typically PET, or virtually any other flat inert insulating film) is laminated onto a mother glass containing a thin adhesive layer. The stack is then taken through the array process, and, once complete, the plastic substrate is removed by a thermal release process. This process is simple and, as a result, has already been shown to have near 100% yield in a factory setting. Additionally, the mother glass itself can be reused multiple times through the line. The relative simplicity of the mount and demount process is one example of how the process flow for OTFT is made simpler because high temperatures are unnecessary. The processes are compared in Fig. 6.

These processing benefits, combined with the mechanical benefits and electrical maturity, give OTFTs a unique capability set for wearable and truly flexible OLED displays (Fig. 7).

Mobile phones and mobile devices may represent the biggest behavioral change of western society in the past 50 years. Wearable electronics have the potential to be the next wave, but need flexible electronics, in the form of flexible displays and sensors, to bring the level of utility necessary to unlock the full market potential. OTFTs offer unrivalled levels of flexibility for AMOLED displays and represent an opportunity for designers to bring completely new levels of user experience and utility to the world of wearable electronics.

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Wearables Challenge the Display Industry to a New Round of Development

Activity trackers, smart watches, and near-to-eye displays represent three major areas of wearable technology. In order to maximize on the potential of any of them, developers must combine forward thinking with enough humility to learn from the past.

by Paul Gray

IN 1916, the British Army faced a dilemma: trench warfare with its creeping barrages made accurate timekeeping in the field a necessity. The words "synchronize your watches" were used for the first time. Pocket watches were unsuitable for trench warfare, so wristwatches, until that time a piece of jewelry worn by ladies, were issued to all officers. As men returned home on leave wearing wristwatches, the devices became viewed not as effeminate but as the very mark of masculinity.

Nearly 100 years later, display and consumer-electronics manufacturers alike are hoping that new types of wearable devices will find that ideal spot where they simultaneously fulfill a need and exist as an object of desire. The consumer-electronics industry is facing bleak days: the flat-panel TV business has peaked; iPad shipments are declining; and, while smartphone volumes are still growing, the best days of profitability – at least in terms of the products we know now – look to be over. What is surprising is that the pipeline of up-and-coming consumer-electronics devices is so empty. What makes it worse is that the smartphone is cannibalizing its way through pre-existing categories such as cameras and navigation (and even wristwatches). The emergence of wearable devices in 2013 and 2014 has, therefore, been seized by an industry hungry for a high-growth product that will provide a high-volume, high-value business for the future. At present, there are roughly three classes of such devices: activity trackers, smart watches, and near-to-eye displays.

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Activity Tracking

Activity trackers are small devices that are usually worn on the wrist, although formats such as belt clips and foot pods are also common. They are essentially data-loggers, using accelerometers to measure movement. Algorithms then interpret the data set as running, walking, *etc*. This enables the wearer's activity level and calorie consumption to be estimated, along with duration of aerobic activity. At the most basic level, a tilt switch and counter can log steps, although more refined versions use barometers to differentiate between climbing stairs and walking on flat surfaces. Adding more sensors improves accuracy, although the data remains an estimate, and some activities are hard to measure: the difference between walking and cycling being one. Such devices generally have simple displays: a paired smartphone, tablet, or computer typically does the heavy lifting in terms of display.

These are behavior-modification devices, and their true power (once the novelty wears off) is in the motivational effect of their apps. Well-written apps are addictive and motivating; poorly created versions give the impression of being bossy and rude.

The potential of such devices as behavior-modification tools is huge, considering the costs to healthcare systems from obesity and inactivity (Fig. 1). The UK health ministry estimates the cost of a heart attack as £50,000 (around $80,000) per person in healthcare alone. Even if only 1% of people in the World Health Organization chart in Fig. 1 changed their lifestyles, the benefits could cover the outlay in seeding everyone with fitness trackers. Such thinking appears to be taking hold in some corporate wellness programs, and companies in behavior-modification businesses such as dieting and weight loss are likely to adopt these kinds of trackers.

Smart Watches

Smart watches are the most obvious wearable product in that they add computing functions to an existing product category. They are inherently different from other wearables in that they are essentially communication devices. Their predecessors, smartphones, have evolved from phones to media-consumption devices and are in essence pocket-computing Swiss army knives. In recent years, their format and especially their screen size have sacrificed portability for improved media consumption. In addition, Apple has educated consumers to appreciate (and demand) a display as good as high-quality magazine printing. Competition did the rest. The phablet category introduced an even larger device that was good for everything but

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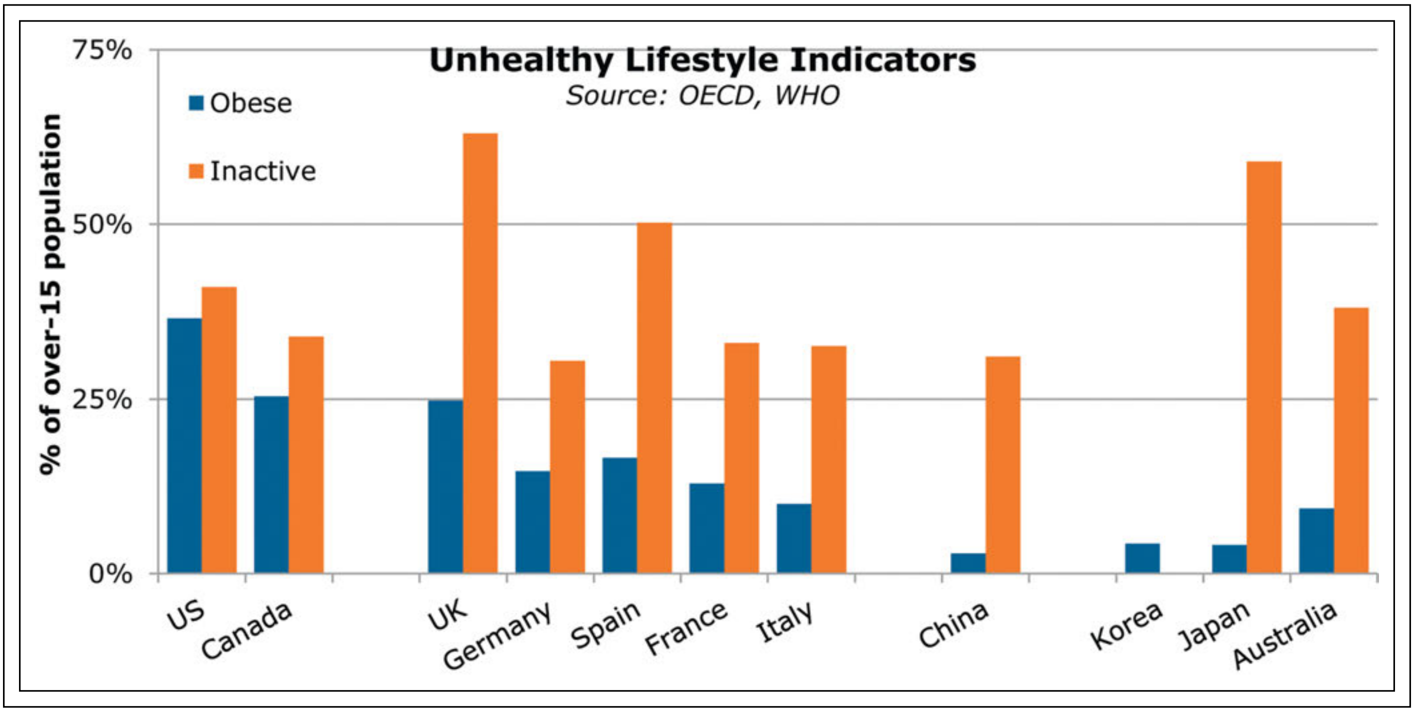

Fig. 1: Obesity and inactivity represent huge potential costs to healthcare systems. Countries where these conditions are prevalent represent potential markets for fitness tracking devices.

holding to the ear as a phone or using while walking.

DisplaySearch research suggests that around 25% of women in Asia have hands too small to hold larger smartphones. Against this background, the smart watch makes some sense. With phones optimized for longer tasks (such as a 5-minute video clip or an email), a gap has emerged in the market for a device targeted at very brief tasks and information. Such tasks include simple, timely information of very high value in a simple format. Imagine being in a rush-hour crowd at a busy railway station: knowing when and where to catch the connecting train would be priceless. Removing a phone from a pocket, entering the code, and then starting the right app in order to obtain this information would be time consuming and difficult in a crowd. A well-designed smart watch could be the answer. From this basic value proposition, manufacturers have used their imagination to add features accordingly: fitness tracking capabilities are popular in smart watches. The final dilemma facing makers is whether to nod to the tradition of watchmaking or fly against it: should smart watches look like watches or take on a completely new aesthetic? Motorola's Moto 360 looks like a watch; Samsung's products are more like smartphones on the wrist, while Apple has ventured somewhere down the middle, with watch-like detailing but a rectangular screen.

Near-to-Eye Displays

Near-to-eye displays are the most futuristic and require the healthiest dose of optimism on the part of developers and users. There are two main types: Google-Glass-type glasses with a head-up auxiliary display providing contextual information and fully immersive virtual-reality headsets intended to present a completely new world that fills the senses. Google did a superb job of publicity with Google Glass, which definitely captured the popular imagination. However, stories about its use reveal a deep truth that societies are not quite ready for such devices.

To begin with, it is illegal to wear Google Glass while driving in most countries. The fact that one man wearing a pair (switched off, just for the corrective lenses) in a cinema led to several hours of interviews with the Department of Homeland Security reveals how much things would have to change in order for these devices to be universally accepted.

Furthermore, national privacy norms differ significantly. Europeans are generally more sensitive than Americans about privacy; wearing Google Glass in a public space in Germany (for example) is likely to meet with a cold reception. Consumers in Germany are very sensitive to being recorded by others, with or without their knowledge. Recent European legislation on the right to anonymity on Google is a case in point, while Google Streetview in Germany has many buildings blurred out at the request of their owners. However, societies that accept such functionality could react positively. The meteorite air burst in Chelyabinsk in 2013 was widely captured on video, largely by dashboard cameras. Such cameras are popular in Russia, as motor insurance fraud is a severe problem.

Necessity is the mother of adoption. As a result, we expect that near-to-eye glasses will be deployed in private premises where they improve productivity or where touching screens or keypads is problematic; sterile environments such as surgery or food processing, as well as production lines, servicing, and warehousing, would seem to be promising candidates. In such applications, the glasses would need to be integrated with the enterprise's data systems and would likely be part of them.

For example, digital signage turned out to be not so much about the display technology as about systems to manage the information – so professional wearables will more be about managing the information presented to the wearer. For an airline customer-service application, the biggest challenge is how to get correct relevant information immediately to the customer services agent: ("Good morning, Mr. Gray, your flight will now depart from Gate 24").

Virtual-reality headsets have been around for a long time; developers seem to assume we all want them more than we actually do – similar to paperless offices. Sega teased with its VR headset from 1991 to 1994, but never released it. There are two main issues that need to be overcome. First, a safe-use area is necessary if people are to wear them without inadvertently falling down stairs or hurting themselves. The second is the challenge of presenting a real experience. The failure of 3-D was caused in part by the brain picking up contradictory sensory cues that caused eyestrain and broke the sense of immersion. In the case of VR headsets, the disparity between balance sensing and vision will cause motion sickness for some and reduce the effect for many more. Furthermore, the fact that Oculus Rift prototypes used a stripped-down Samsung smartphone and Google's cardboard smartphone mount suggests that the category is wide open to cannibalization, at least in the high-volume consumer segment.

In considering this market, it is vital not to forget people! The moment something is worn it becomes a part of personal identity. People want to look individual and different. They identify so strongly with smartphones that they customize them with cases unlike the matte gray Nokias of the 1990s. The wearables market is inherently different from consumer electronics in that product diversity is good. Therefore, it is likely to have far more niches in design, construction, and materials: "One size fits all" will not work. Amazon.com currently has over 300,000 watch models for sale; Casio has over 1500 live watch products. Prices range from $10 to over $100,000, and the device design transcends function. For smart watches, displays are part of this differentiation, from the watch-like round face of Moto 360 and G-Watch R to the rectangular screen of Samsung's Gear S.

With design being a greater factor than for other consumer-electronics types, we expect that competition will play out a little differently. It appears unlikely that a single company can dominate in the "winner takes all" dynamic of phones. Instead, this is more likely in operating systems because smart watches are essentially software devices. So the balance is likely to favor more hardware variety but based on standard platforms. Apple's challenge will be to satisfy its consumers' desire for individuality.

Different Scenarios for Success

Unsurprisingly for such a new product type, display technology is not yet mature and no technology is clearly superior. While consumers have been educated to want a bright, sharp, high-contrast display, the biggest constraint on designers is trading off bulk and battery size. Features of questionable value in applications such as TV have real benefit in wearables: curved screens enable products to fit more closely and naturally while bendable displays promise to be more comfortable and

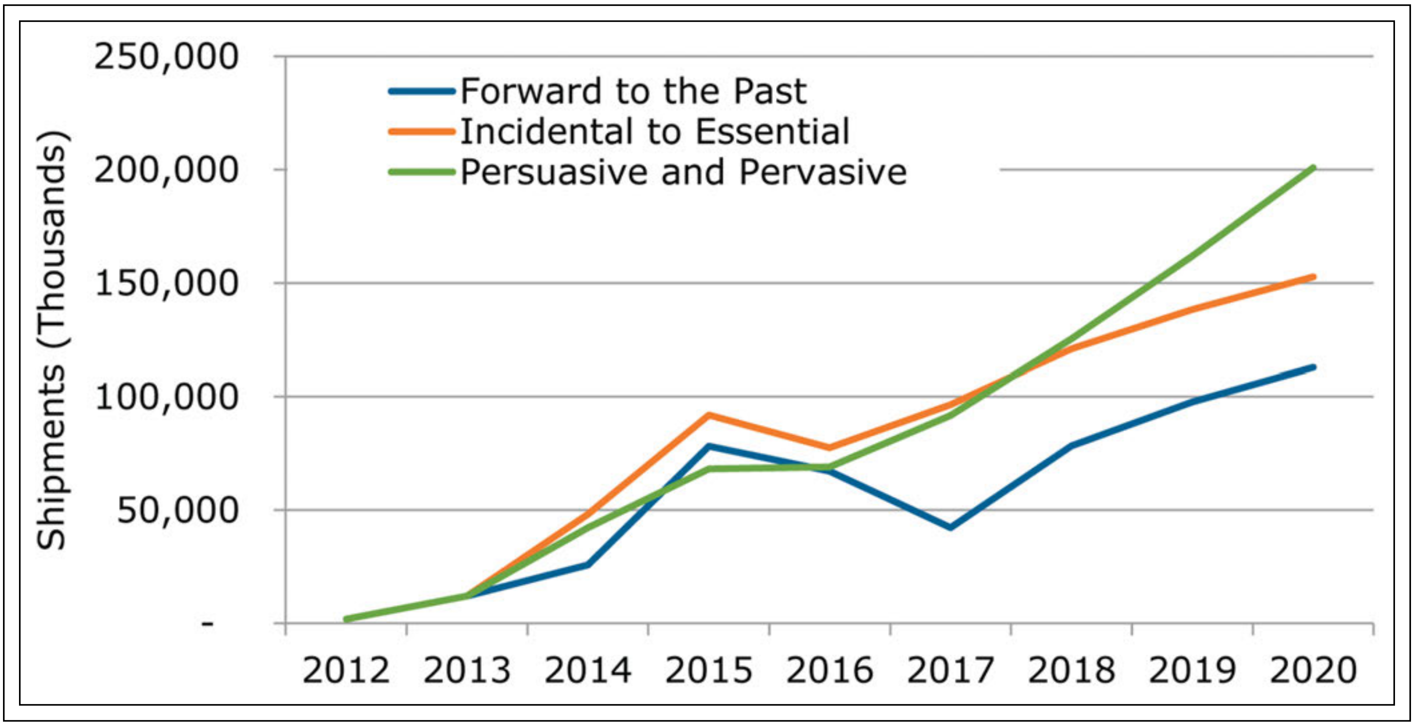

Fig. 2: DisplaySearch has created three potential scenarios for the wearables market through 2020. All show growth, but the "Persuasive and Pervasive" model shows the steadiest and highest long-term growth.

robust. Depending on the designer's intention, almost every technology has its place. For a long-lasting light device, then e-Paper or bistable LCDs are optimal; for a colorful display on a smart watch with a bold high-tech statement, AMOLED displays would be more appropriate. Interestingly, some technologies that have been recently out of favor, such as e-Paper and passive-matrix OLED technology, can expect a re-appraisal as they create new opportunities: e-Paper enables a breakthrough to the power problem, enabling a light, thin watch, while PMOLED technology provides a low-cost punchy curved or flexible display for simpler devices.

The biggest challenge for designers and product managers is deciding what part of the market to address and how to tailor an optimal product. The usual consumer-electronics industry habit of adding features will be severely punished by poor usability and short battery life. Consumers are a poor guide: many consumers we interviewed wanted video capability – yet a 1-in. screen would be almost unwatchable and most of us would pick the phone from our pockets instead to watch video. Savvy product managers will decide on a few functions to do well, be it a device optimized for specific sports by its motion-capture algorithms and form (*e.g.*, waterproof for swimming, impact resistant for squash) or for an ultra-thin and stylish band with an OLED display and jewelry standard of finish.

DisplaySearch has constructed several scenarios in which to explore market development. In all scenarios we have modeled some elements of hype. Wearables are in part fashion items and some consumers will purchase them simply to have the latest thing. Our three scenarios appear in Fig. 2.

In the "Forward to the Past" scenario, a strong fashion surge will be followed by cannibalization from smartphones, which remain dominant. Fitness bands prove transient as consumers use tracking apps in their phones or add small transponders for exercise. "Incidental to Essential" has a fashion element, but growth is underpinned by strong platforms that command consumer loyalty, such as Android Wear and iOS. This scenario also assumes that fitness devices establish a lasting place in the market. For "Persuasive and Pervasive," the initial hype is very limited, as consumers struggle to understand why they need wearables. Adoption is driven instead by healthcare providers, sustaining long-term growth. However, the market adopts a more business-to-business nature.

Underpinning the scenarios is the knowledge that fashion is a double-edged sword: the bigger the surge, the greater the risk of a crash afterwards. A huge hype for smart watches with poorly thought-out value propositions runs the risk of consumers confining the devices to a drawer after a few months' frustration. If that happens, the smart watch will be a repeat of the digital photo frame or 3-D debacles, where over-promoted products of little lasting value hit the market and then fizzled.

In my personal experience of wearables this year, I have found some surprising things. Of three fitness trackers, two have been lost relatively quickly when their straps popped open. One was a direct result of its addictive app – I decided to see what it would make of kayaking as exercise; the other disappeared somewhere between the jet bridge and baggage reclaim in an airport. However, my trusty Casio LCD chrono watch has survived 20 years of sailboat racing and salt water. Wearables makers need to have the humility to learn from a century's experience in making wristwatches and adopt a few of those tricks in building the category. The potential health benefits are huge, and the need is there. Imagination will be the key to the next step – and display technology has its part to play as the very face of the product. ■

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Looking to meet up with your colleagues in the display industry to discuss technology, business, or just socialize? The events below present just that type of opportunity:

Annual Awards Dinner, Monday:

Each year, SID recognizes individuals that have played a critical role in improving the display industry. This year's winners will be honored at an awards banquet taking place the evening of June 1 at the San Jose Convention Center.

Business Conference Reception, Monday:

Follows the Business Conference, please note conference attendance is required for admission.

Annual Award Luncheon, Wednesday:

The annual Best in Show and Display Industry Awards Luncheon will take place at noon on Wednesday, June 3. Both awards are peer-reviewed, such that the luncheon is well-attended by captains of industry for high-level networking and recognition of the best in the industry over the last year.

Investors Conference:

The IC will feature presentations from leading public and private companies in the display technology supply chain and encourage questions and discussion between presenters and participants. Concludes with Drinks & Displays: Networking Reception with Presenters and Investors

Market Focus Conference Reception, Wednesday:

Follows the Wednesday Market Focus Conference, title and program TBD, please note conference attendance is required for admission.

The Pursuit of Innovation

The Japanese display industry has been challenged by competition from overseas, the elimination or downgrading of previously successful product categories such as plasma TVs and video cameras, and an uncertain national economy. Both the public and private sectors are betting on the power of innovation to help the display industry and the rest of the Japanese consumer-electronics industry rise to the top once more.

by Jenny Donelan

EVEN as U.S. companies have lost consumer-electronics market share to other countries in recent years, they have been able to console themselves with the thought that, "Well, at least we're the innovative ones." However, the country that gave birth to Google, Facebook, and the iPhone has now been surpassed in terms of innovation, at least according to the list of 2014 Top 100 Global Innovators recently announced by Reuters. The country that is now home to the largest number of innovative companies in the world is Japan.[1]

According to the report: "Despite years of economic stagnation, Japan is still the world's third largest economy with a predominantly high-tech output of inventions. Expenditure on R&D as a proportion of GDP, having dipped in 2010, has returned in recent times to historical levels of approximately 3.4%. Compared to the U.S. (2.7%) and Europe (2.0%), there is a significantly higher level of investment in innovation, as is reflected in the higher presence of Japanese companies in the Top 100 listing this year."[2]

Although it should be noted that the winning companies were named based on their R&D investment rather than for particular products, that level of investment is significant. And of those winning companies, the ones with display-related products or services include Asahi Glass, Denso, Fujitsu, Hitachi, Kyocera, Mitsubishi, NEC, Nitto Denko, Panasonic, Ricoh, Seiko Epson, SEL, Sharp, Sony, and Toshiba. So it is encouraging to see that Japanese industry, with a strong background in a display industry that has been faltering of late, is putting R&D money behind-display-related companies.

Jenny Donelan is the Managing Editor of Information Display *magazine. She can be reached at jdonelan@pcm411.com.*

A Tumultuous History

Before discussing the display industry in Japan, it is instructive to back up a bit and look at the nation's industry as a whole. Few countries have an industrial history as storied as Japan's. This small island country (about the size of California) has enjoyed the world's second-largest economy throughout much of the Cold War era and beyond. Although some of that success was due to post-war assistance from the U.S., the major factor has been the country's unique economic policy, which ensured close cooperation among government bodies, manufacturers, banks, unions, *etc*.[3]

Beginning in the 1950s, the Japanese industry embarked on a long journey to quality, as industrialists began to experiment with the statistical quality concepts of American theorist Dr. Edwards Deming and other management consultants. Interestingly, Japanese companies took these theories much farther than their American counterparts, to great success so that some years later, American companies began traveling to Japan to review operations at companies like Toyota.

Beginning with the bursting of a bubble economy in 1991, Japan experienced a profound and lasting economic slump that it is still struggling to emerge from. The 1990s are sometimes referred to as "the lost decade," but the 2000s were only marginally better. As this article went to press, the country had just re-elected Prime Minister Shinzo Abe, suggesting national approval of his last 2 years' efforts to revive the economy. While the current low value of the yen has attracted many tourists to Japan and in some ways invigorated the economy, big changes would appear to be afoot following Abe's re-election. His plan to reinflate the economy after 20 years of deflation (referred to as "Abenomics") is actually more popular with economists than the Japanese public, according to a recent article in the *Financial Times*.[4] But some experts are predicting boom times ahead for Japan, especially now that Abe will be in office until 2018, giving him a good stretch of time in which to execute his plan.

Despite its recent struggles, Japan is still the third-largest economy in the world,[5] the third-largest automobile manufacturer in the world,[6] and the third-largest shipbuilding nation.[7] As recently as 3 years ago, it was the largest consumer-electronics maker in the world.[8] Though it still ranks high, there is no doubt that in recent years Japanese consumer electronics has taken a hit from China and South Korea, which have surpassed it both in terms of flat-panel and smartphone produc-

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tion. In addition, products such as video cameras and still cameras, former mainstays of the Japanese consumer-electronics industry, have become less popular, partly because their functions have been taken on by cell phones. Even Japan's once-invincible gaming industry is considered to be in decline – a far cry from the 1980s and 1990s when Nintendo and Sega dominated in terms of both games and devices.

The Business of Displays in Japan

Obviously, the success and failure of any consumer-electronics business is closely related to displays. Japan has a proud history in both display research and commercialization, with countless Japanese scientists contributing to developments in CRTs, LCDs, and OLEDs. Last year, for example, Sharp researcher (and former Hitach researcher) Katsumi Kondo won SID's Karl Ferdinand Braun prize for contributions to in-plane switching for TFT-LCDs. Both Sony (with its groundbreaking Trinitron CRT television) and Panasonic have long been synonymous with high-quality televisions and audio-visual equipment. Both companies are currently fighting it out in terms of 4K market share, and also with regard to the new "high-resolution audio" format. And it cannot be forgotten that Pioneer and Panasonic were at the top of the flat-panel plasma market until plasma lost out to less-expensive more-pervasive LCD flat panels.

These LCD-based flat-panel TVs, as previously mentioned, became a major source of competition from both Korea and China. According to Kazuhiko Kubota, manager of marketing communications for display company Japan Display, Inc. (JDI), "Display companies in Korea and China scaled up after the products became easier to mass-produce. Large-sized LCD production in China is one example. This does affect display operations in Japan."

How the Japanese display industry has chosen to respond is by concentrating on small-to-middle–sized high-resolution LCDs. Says Paul Semenza, display-industry consultant and former president of DisplaySearch, "In general, Japanese suppliers are focusing on high-end products. JDI is using LTPS, IPS, and in-cell touch to address high-resolution smartphones and is moving into tablet PC panels; Panasonic is somewhat of a niche supplier. While Japan has a very small share of the large-panel market (less than 10%), Sharp and JDI are number three and number four in the small-to-medium–sized market."

JDI itself is the result of a 2012 merger of Sony, Toshiba, and Hitachi's LCD divisions (financed by the Innovation Network Corporation of Japan, about which more later) that was created to pursue this very market. Kubota says his company's focus is on high-value advanced LCD applications for the mobile, automotive, and commercial and industrial display markets in particular.

Other Japanese display companies involved in the small-to-mid–range area are Sharp, Semiconductor Energy Laboratory (SEL), and Advanced Film Device, which together developed a 13-in. OLED screen with 8K resolution that was shown at last year's Display Week (Fig. 1). The display has 7680 × 4320 pixels, with a density of 664 pixels per inch (ppi).

Sharp is an example of a Japanese company that is clearly pursuing innovation. Both Sharp and SEL won a 2013 Display of the Year Gold Award from SID for joint development of an indium gallium zinc oxide (IGZO) display with both high resolution and ultra-low power consumption. Although researchers around the world had pursued IGZO as a backplane material for some time, Sharp was ahead of the curve in finding commercial success with it. Its IGZO technology was first used in its Aquos smartphone. In 2013, Apple released a version of the iPad Air that was IGZO based. Although not officially confirmed (as is the case with Apple's suppliers), this IGZO is assumed to be Sharp's. According to Semenza, Sharp is using oxide TFTs on its Gen 8 line to address larger higher-resolution tablet PC markets. In addition, it is using its Gen 10 line to make large (70-, 80-, and 90-in.) LCD TV panels.

In June of 2014, Sharp announced what it calls its Free-Form Display, which can be configured in a variety of shapes, such as circles and ovals. These displays are based on IGZO technology and proprietary circuit design methods that enable gate-driver functions to be dispersed throughout the pixels on the display area, rather than the perimeter. This functionality is clearly aimed at the dashboards of cars, among other applications.[9]

According to a recent article in the *Financial Times*, Sharp says that it too has shifted some of its focus to the smaller- and medium-sized displays used in smartphones and tablets and hopes to increase sales for displays used in vehicles. The Japanese manufacturer also says

Fig. 1: *Sharp, SEL, and Advanced Film Device collaborated to create an impressive high-resolution 13-in. OLED panel that was shown at Display Week 2014. Source:* OLED-display.net.

it is trying to avoid making the same mistakes with car screens as it did with TV displays. Some experts have said that Japanese TV manufacturers lost touch with consumers as they became obsessed with improving picture quality, while Asian rivals offered less-expensive sets with display performance that was lower but good enough to satisfy viewers.[10]

Last summer, Sony and Panasonic teamed up with JDI to create a new company to design medium-sized OLED panels. The company, JOLED, was also financed by the Innovation Network Corporation of Japan (INCJ). The venture will integrate Sony and Panasonic's OLED R&D functions with JDI's wide portfolio of display technologies. The company is expected to go live in January 2015.[11]

Another company that has been investing time and money in OLEDs, though in the area of lighting, is Konica Minolta. At Display Week 2014, the company presented what it claims is the world's most-efficient OLED panel, with an emitting area of 15 cm^2, a lifetime of 55,000 hours (LT50) at a brightness of 1000 cd/m^2, and a CRI of 81.[12] The color temperature is 2857K. Konica Minolta has also started roll-to-roll manufacturing of flexible OLED panels using a plastic barrier film. This is currently the world's largest manufacturing line (Gen 5 equivalent) for OLED lighting.[13]

8K Possibilities

Even as consumers are learning about 4K resolution, work is being done at the R&D level on 8K resolution. Japanese public broadcaster Nippon Hoso Kyokai (NHK) has been a proponent of 8K content for some time. (See the article by NHK, "Super Hi-Vision as Next-Generation Television and Its Video Parameters" in the November/December 2012 issue.) NHK held public 8K viewings in Brazil and Japan of World Cup soccer matches last year. This knowledge of 8K from a major Japanese content provider could prove some useful synergies with Japanese display makers in the future.

Investing in Innovation

The Innovation Network Corporation of Japan (INCJ), having been instrumental in the formation of two new display companies, could well play a key role in the display industry's future. It also represents the kind of wide-scale long-range government involvement in the country's industry as a whole (similar to post-World War II) that is a key differentiating factor for the Japanese industry. According to the INCJ website, the organization was designed to "provide financial, technological, and management support in order to promote the creation of next-generation businesses through 'open innovation,' or the flow of technology and expertise beyond the boundaries of existing organizational structures. The organization is now actively reviewing various investment opportunities in areas of green energy, electronics, IT, and biotechnology to infrastructure-related sectors such as water supply."[14]

Clearly, Japanese companies, and not just the government, are aiming at innovation for redemption. When asked about the role of the Japanese display industry on a global level, JDI's Kubota responded: "The role of Japan's display industry is to lead in innovating technologies for display panels, related materials, parts, and production facilities." And, certainly, Japan's display history is rich in innovation, with Japanese companies pioneering the first mass-produced laptops (Toshiba) and LCD screens (Sharp).[8]

Just where that innovation will lead is the question. Perhaps a hint of what's ahead could be found in the innovation awards at the most recent CEATEC JAPAN. CEATEC is Japan's largest consumer electronics show. The CEATEC Innovation Awards are made by U.S. journalists. According to the awards website, "This year's CEATEC JAPAN was quite different than its predecessors. In prior years, the show was dominated by consumer-electronics products. Vendors competed to unveil the largest screens. While television and 8K technology was present at the show, this years' conference was dominated by displays for components, Big Data applications, and robotic technology."[15] Chief among this year's display winners was Toshiba Glass, a simpler lighter Google Glass rival. The Grand Prix winner was not a display but a table-tennis robot that functions as an actual opponent.

As for rumors of its demise as an economic superpower, they are premature. Japan continues to do quite well. Japan's display industry itself has several factors in its favor. One is the country's overall history of consumer-electronics excellence. Another is the willingness of different industry entities to join together in a common cause and the willingness of government to support those efforts. The formation of JDI, for example, was not a reactive cost-cutting measure, but a proactive measure designed to meet the competition.

Last, it should not be overlooked that Japan is the land of outrageous fashion trends and inventions. The JapanTrends.com website has an entire department dedicated to product innovations, which range from socks that resemble sushi to paper masks that read and display with symbols the kind of mood the wearer is in. It is easy to poke fun at some of these inventions, but out of such playfulness does innovation come. It's impossible to say whether the next disruptive display device will come from Japan, but with imagination, the willingness to adjust and cooperate, and a government willing to provide the resources, it just might happen.

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2015 EDITORIAL CALENDAR

■ January/February
Flexible Technology, e-Paper, Wearables
Special Features: Wearables Update, Flexible Technology Market Overview
Related Technologies and Markets: e-Paper, substrates, films, coatings, OLEDs, manufacturing, wearables
Sept 1: Editorial content proposals due
Jan 5: Ad closing

■ March/April
Display Week Preview, Topics in Applied Vision
Special Features: SID Honors & Awards, Symposium Preview, Display Week at a Glance
Related Technologies and Markets: Projection, LCDs, OLEDs, metrology, wearables
Nov 3: Editorial content proposals due
Mar 6: Ad closing

■ May/June
Display Week Show Issue, Automotive
Special Features: Display of the Year Awards, Products on Display, Market Overview of Automotive Trends
Related Technologies and Markets: LCDs, OLEDs, projection, ruggedization, manufacturing, automotive, marine
Jan 5: Editorial content proposals due
May 1: Ad closing
Special Distribution: Display Week 2015 in San Jose and IMID in Korea

■ July/August
Interactivity/Touch/Tracking, Portable Technology
Special Features: Portable Devices Study, Touch Market Update
Related Technologies and Markets: Materials, ITO, ITO replacements, backplanes, glass, films, tablets, smartphones
Mar 2: Editorial content proposals due
June 30: Ad closing
Special Distribution: Vehicle 2015 and EuroDisplay in Belgium

■ September/October
Display Week Wrap-up, Metrology
Special Features: Display Week Technology Reviews, Best in Show and Innovation Awards, Metrology Update
Related Technologies and Markets: Measurement, spectrometers, LCDs, OLEDs, quantum dots, manufacturing
May 4: Editorial Content Proposals due
Sept 2: Ad closing
Special Distribution: IDW in Japan

■ November/December
3D/Holography, Television
Special Features: Consumer TV Roundup, State-of-the-Art 3D Survey
Related Technologies and Markets: OLEDs, LCDs, TVs, Retail Electronics
July 1: Editorial content proposals due
Nov 3: Ad closing

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editorial

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Carrying is inconvenient, however, so the next step is to make these devices wearable and hence an extension of our clothing or body. Watches and glasses may be obvious, but I think they are just the tip of a potential iceberg. To give you a taste of what's out there, our own managing editor Jenny Donelan penned an Enabling Technology feature that provides a sampling of available devices. Jenny takes a look at a number of currently popular categories and offers some perspective about how each one looks today and where they might be heading in the years to come.

Taking a deeper dive into the underlying technology, we have a trio of Frontline Technology articles developed by our Guest Editor Ruiqing (Ray) Ma, Director of Flexible PHOLED Lighting at Universal Display Corp. Ray has done a great job covering several important aspects of flexible and wearable technology. He introduces it to you in his guest editor's note titled, "Get Ready for Another Form-Factor Revolution." I suggest you read this first for context and then go to the accompanying articles. It's interesting to see that in these reported efforts, the display technology of choice is OLED, not LC. That seems to be a trend that goes along with making things thinner and more mechanically robust. That is not to suggest that there is no further interest in flexible LCDs, but in this portable and wearable device space, the latest work seems to be focused on OLED displays.

The display business is truly a world-wide enterprise, and this month we take a look at the state of the industry in Japan in our Regional Business Review titled, "The Pursuit of Innovation," also written by Jenny Donelan. Jenny looks back at the last half-century of Japan's economic history to set the context for where they are today and then offers some analysis of what the future might hold. As she rightly points out, despite some recent challenges, Japan's ability to combine government and private enterprise in the right proportions ensures that the investments in innovative products and technologies, including displays, will continue unabated. If I had money to invest, I would be looking closely at Japan's tech companies for good opportunities.

We complete our offerings this month with our Display Marketplace feature, "Wearables Challenge the Display Industry to a New Round of Development," written by DisplaySearch analyst Paul Gray. Paul's wealth of information and experience enables him to take a thoughtful view of the prevailing applications today and their challenges as well as offering some advice to product managers for future success.

One thing that has struck me in the last year or so is how quickly current product designs have moved away from low-power display technologies like electrophoretic technology. I still use my original Kindle almost every day for reading and it still lasts over a week on one charge. When looking at non-video applications such as fitness trackers, health monitors, or watches, as Paul also suggests in his article, that there could still be room for reflective displays to make these devices more reliable and less power hungry. Electrophoretic technology is inherently flexible, and if paired with the right flexible TFT backplane could still have some life in it in a new product category, just as it helped bring e-Readers to life. That's just a suggestion for someone in the innovation department to take a closer look.

So, thanks to our authors, guest editor, and staff for working so hard on this issue, and I hope it stimulates some new creative ideas out there in our industry. Happy New Year, everyone! ■

guest editorial

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Finally, we come to wearable devices. I asked experts at Plastic Logic to help us better understand wearables by answering the following questions: (1) what are wearable devices; (2) what are the display requirements for wearable devices; and (3) what can flexible displays offer to wearable devices? In the article titled, "OTFT Can Unlock the Potential of Wearables," Dr. Paul Cain and his colleagues not only provide answers to my questions (check out their solution for battery life), but also report their work on flexible AMOLED displays using organic thin-film-transistor (OTFT) backplanes for wearable applications. At Display Week 2014, they demonstrated their TFT array that can be curved around a 250-μm radius (*i.e.*, around a matchstick) with no change in transistor performance. They believe that OTFT offers unrivaled levels of flexibility for AMOLED and represents an opportunity for designers to bring completely new types of user experience and utility to the world of wearable electronics.

I believe these three articles provide a good idea of the current status of flexible AMOLEDs in both technology and application development. Of course, we still face challenges, as explained by all three articles, and will continue to do so. But if there is anything I have learned over the years, it is that you can never underestimate the resolve and capability of the great people and companies in this society and industry. If the consumers want it, we can make it. With flexible displays, we also expect to see entirely new design platforms, and who knows what new products will be created.

As a final thought, I again take you back to 1995 on a Tuesday evening at the Walt Disney Dolphin Hotel. First year in graduate school and just entering the field, as I sat in the audience of a panel discussion titled, "Can FPDs Replace CRTs?," I had no idea I was already on the amazing ride that was the first display form-factor revolution. Twenty years later, I am quite prepared for the second.

Enjoy the ride. ■

***Ruiqing (Ray) Ma** is Director of Flexible PHOLED Lighting R&D at Universal Display Corp. He can be reached at RMA@udcoled.com.*

EuroDisplay 2015 Call for Papers

The organizers of EuroDisplay 2015, which takes place September 21–23 in Ghent, Belgium, are now soliciting papers. Suggested topics include Display Materials, Display Applications, Additive Manufacturing, Metrology, Displays and Lighting, OLEDs and Organic Electronics, and Liquid Crystals Beyond Displays. However, the submission of papers dealing with any aspect of information displays is highly encouraged. Abstracts are due April 1, 2015.

EuroDisplay, which is sponsored by the Society for Information Display, is also being organized by Ghent University this year and, in particular, by two of its research groups: the Centre for Microsystems Technology and the Liquid Crystal & Photonics Group. EuroDisplay is part of the IDRC (International Display Research Conference) series of SID-sponsored conferences and is slightly more focused on academic research than on product development, as compared to a conference such as Display Week.

"EuroDisplay has a more intimate look and feel than [for example] the SID symposium or IDW," says General Chair Herbert De Smet, adding that the number of parallel sessions is smaller, making it easier to attend all the sessions of interest. "EuroDisplay is a conference on a human scale and in a unique setting, facilitating easy networking and allowing for in-depth discussions of display-related research topics," he says. This year's unique setting is Het Pand, a former monastery owned by Ghent University that is located along a channel in the medieval center of Ghent. Ghent itself is a charming city and hidden gem, named one of Lonely Planet's top 10 cities to visit in 2011 (Fig. 1).

Keynote speakers at EuroDisplay will include Ian Underwood of the University of Edinburgh, who will speak about the commercial track record and potential of European display research in the global market; Kayvan Mirza from Optinvent, who will discuss wearable displays as the next mobile paradigm; and Nelson Tabiryan of Beam Company, whose topic will be "The Fourth Generation of Optics."

According to the conference organizers: "We aim to make EuroDisplay 2015 the ideal place for networking between all involved in display-related research and development. The conference will be a mixture of presentations by academia and industry with a showcase of new display technologies during the exhibition."

For more information about EuroDisplay 2015 and to submit an abstract, visit www.sideurodisplay.org. General Chair De Smet can be reached at Herbert.DeSmet@elis.UGent.be.

***Fig. 1:** Ghent, Belgium, site of EuroDisplay 2015, is renowned for its medieval architecture. St. Michael's Bridge, lower right, is a famous landmark. Image courtesy* www.visitgent.be.

Futaba Takes Inaugural Best-in-Show Award at Vehicle Displays

Futaba Corporation of America won the first-ever Best-in-Show award at the 20th Annual Vehicle Displays and Interfaces Symposium and Exhibition held in Dearborn, Michigan, last October. Futaba is a maker of displays and touch-screen products for automotive, medical, industrial, and consumer markets. The award went to the Futaba exhibit for its demonstration of a range of products, including its "mature" vacuum fluorescent displays, its OLED technology, and its capacitive touch panels (Fig. 2).

Of particular interest, noted awards committee member Silviu Pala, was Futaba's new OLED technology for vehicle panel knobs, which allows a dead-front design with a true black background. "The issue with LCD technology," says Silviu Pala, "is that you can see the outline of the square display [due to the backlighting]." OLED displays eliminate the square look at a cost lower than that of TFT-LCDs, he adds. Robert Dohring, Senior Automotive Sales Manager at Futaba, explains that OLED displays are less expensive from a system standpoint because as an emissive technology they do not require the backlighting, bezel, and other components needed for an LCD.

The winning exhibit was chosen among 32 on hand at the 20th annual event. A panel of experts, led by the executive committee of the Michigan Chapter of the SID, made the decision.

***Fig. 2:** Futaba Corporation of America's exhibit won the first-ever Best-in-Show award (see ribbon at right) at the 2014 Vehicle Displays and Interfaces exhibition. From left to right are Jeff Hatfield, Automotive Engineering Manager; Makoto Akira, Engineering Manager, Strategic Development; and Robert Dohring, Senior Automotive Sales Manager.*

— Jenny Donelan

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Radiant Zemax Sells Zemax Business Unit

Radiant Zemax, a provider of integrated systems for light and color measurement, recently announced the sale of its Zemax optical design software business unit to Arlington Capital Partners.

Not too many years ago (2011), Radiant Imaging and Zemax Development Corporation merged to form Radiant Zemax, a portfolio company of Evergreen Pacific Partners. According to the official announcement from Radiant Zemax,[2] the merger brought together complementary technologies and enabled the new entity to invest heavily in Zemax's flagship product, OpticStudio, which has delivered what the company terms "unprecedented" growth. As an independent standalone business, Zemax will focus on its core customers and technology.

The Radiant division will remain an Evergreen Pacific Partners portfolio company but announced in mid-January that it would begin operating as Radiant Vision Systems.

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[2]http://www.radiantzemax.com/rz/news/New-Press-Release-Article ■

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