MATERIALS AND FLEXIBLE TECHNOLOGY ISSUE

Information DISPLAY

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Is This the Future of Displays?

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ON THE COVER: Sepia apama, *also called the Australian giant cuttlefish, is one of many cephalopods that can change the appearance of its skin in an instant, creating one of nature's more intriguing displays. Image courtesy Roger Hanlon, Senior Scientist & Director, Program in Sensory Physiology & Behavior, Marine Biological Laboratory, Woods Hole, Massachusetts.*

Cover Design: Acapella Studios, Inc.

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editorial

New Year, New Innovations

by Stephen P. Atwood

Happy New Year and welcome to 2014. We saw a lot of exciting things in 2013, including a near miss with an asteroid, confirmation of water on Mars, more record-breaking weather here on earth, and the further embedding of technology in our daily lives. The display industry saw encouraging signs of better economic times to come and more new innovations than I can remember seeing in a long time.

Of course, as I wrote about in November, we finally saw the commercial launch of large-format OLED TVs. This much anticipated milestone was an important vindicating step for those companies that have invested so much in research, development, and infrastructure to get products into consumers' hands. But if you followed along in *ID* for the past year, OLED TVs were only one small part of a great many advances we saw and reported on. We also saw our first Display Week event held outside the U.S., in Vancouver, British Columbia, Canada – which also happened to be our 50th SID Symposium and Exhibition. I did not attend all 50, but I've probably been to at least half of them by now. Vancouver was a great destination and San Diego will be just as much fun with even more new things to see and do.

This year begins our second with the new six-issue calendar. The amount of great contributions from all over the display industry continues to grow and our backlog continues to grow too. We try to pick the very best topics from everything we see, and some become running themes we cover for many issues or even across multiple years. As we look into 2014, we are anticipating a variety of interesting topics, including our regulars such as touch/interactivity, LCDs and OLEDs, metrology, materials, and flexible displays. We also expect to see more great advances in some recent hot topics such as 3D/holography, oxide semiconductors, and paper electronics. Our full calendar for 2014 is available on the Web site.

Our issue themes this month revolve around materials, flexible displays, and e-paper. By now you have probably already noticed something different about this first issue of 2014. Our cover features one of the most interesting creatures in nature – the cuttlefish. Why, you ask, would we feature a rather strange looking mollusk on our cover and what does it have to do with displays? Well, we were asking ourselves the same question until we read the first draft of our cover story, "Dynamic Displays in Nature," by authors Lydia M. Mäthger and Roger T. Hanlon from the Marine Biological Laboratory in Woods Hole, Massachusetts. Cuttlefish, squid, and octopus belong to a class of cephalopods that are able to change the pattern and color of their skin in remarkable ways for both camouflage and communication. Similar to chameleons, these creatures have biological mechanisms in their bodies that allow their skin to literally be a type of display. As we search for new and innovative ways to create flexible displays, there may be many exciting things we can learn from nature, and this article reveals the secrets of how these intricate biological skin-displays really work.

It's not a new concept, borrowing from nature for cues for display research. Countless optical and material science discoveries have been based on observations of the natural world. One example is the principle for Microelectromechanical Systems (MEMS) displays developed by Qualcomm, which is based on the same natural phenomenon that makes a butterfly's wings or a peacock's feathers shimmer and reflect the sun's light into highly diverse and saturated colors. So, it's really no surprise that we may someday make displays with the same principal methods as nature

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Novasentis Wins CES Award for Haptic Actuator

Novasentis, Inc. (formerly Strategic Polymers Sciences) recently won a 2014 CES Innovations Design and Engineering Award in the Embedded Technologies category for its Electro-Mechanical Polymer (EMP) actuator and sensor technology. The Novasentis polymer technology (described in this month's Frontline Technology feature, "New Electro-Mechanical Polymer Actuator Technology for Better Interactivity"), is designed to provide mobile and wearable devices with so-called "co-located" vibrations, movement, morphing, and sound. When a user touches a screen embedded with the charged polymer, an electrical current is generated that creates a range of different vibrations. Novasentis claims its product is the world's thinnest actuator. Last fall, the company announced a Series B funding round of $8 million with new investors Samsung Venture Investment Corporation (Samsung Ventures) and Chengwei Capital.[1]

[1]http://www.businesswire.com/news/home/20131101005218/en/Novasentis-Announces-8-Million-Series-Funding-Change

More 2014 CES Innovations Awards

Additional CES Innovations Awards winners with display components include Instabeat, a waterproof head-up monitor from the company of the same name (Fig. 1) and Tobii Technology's EyeMobile. Instabeat tracks, stores, and displays instant feedback of a wearer's heart rate during a swim.

The EyeMobile is a lightweight accessory that enables eye-control capabilities on Windows 8 tablets, giving individuals with mobility challenges a hands-free way to enjoy tablet functionality.

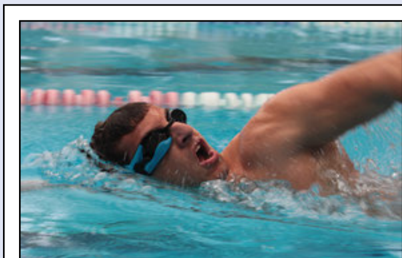

***Fig. 1:** The Instabeat was created by a sports-technology startup in Lebanon whose founder is a former professional swimmer.*

3M Introduces Three New Sensor Films

3M has announced the launch of three new sensor films that bring the company's product line "from the back to the front of displays," in the words of Erik Lood, Marketing Manager for 3M's Electronic Solutions Division. (3M's focus has to date been more on optical films.) The new films include an unpatterned indium tin oxide (ITO) film for high-volume touch-sensor films and a patterned silver nanowire film with conductors made from partner Cambrios's silver nanowire ink and micropatterned by 3M on a polyester (PET) film substrate. The third offering is a highly flexible metal-mesh material designed to enable curved and foldable touch-screen designs.

3M's Advanced ITO Film is an etchable touch sensor aimed at panel manufacturers seeking excellent optical transparency and high conductivity at competitive prices. The 3M Silver Nanowire Film is highly transparent and can support touch screens suitable for phones and tablets, as well as large-area applications such as signage and gaming. Unlike ITO products, the flexible silver nanowire material can conform to angles and rounded surfaces. The 3M Patterned Metal Mesh film offers high conductivity and transparency in an exceptionally flexible material, and its random mesh patterning creates very little moiré. The ITO film became available in December 2013. The silver nanowire and metal-mesh films are scheduled for Q1 2014 availability.

Tactonic Introduces Prototype Pressure Sensing Touch Display

Tactonic Technologies, a maker of pressure-sensing multi-touch and pressure imaging sensor components, has demonstrated a new approach to providing touch for use with flexible displays using a flexible OLED display from the Flexible Display Center at ASU. This touch assembly stack has the sensor under the display rather than as a transparent top layer.

Benefits of the new technology, according to Tactonic, include no optical degradation of the display due to touch layers, lightweight durability and low power, operation via gloved or bare hands, operability under harsh conditions and broad temperature ranges, and no significant EMI issues. The sensor is a mechanically interpolated pressure imaging grid, says Gerry Seidman, CEO of Tactonic Technologies, who adds, "Because of the mechanical interpolation, we can do very sparse sampling and still maintain high positional accuracy."

Applications for the sensors are broad, says Seidman, and so far the company's technology is in commercial use in a smartphone peripheral and also in some non-display automotive applications that will be revealed at CES. In the near future, Seidman expects to see the technology used with OLED, electrophoretic, and other flexible displays that would benefit from this type of sensor.

Foxconn Will Build Factory in Harrisburg, PA

Foxconn Technology Group, the Taiwan-based company that makes Apple's iPhone 5s, among other consumer electronics, is planning to spend $30 million on a manufacturing facility in Harrisburg, Pennsylvania, according to a recent Bloomberg News report.[2] The new facility will employ approximately 500 people. To put that in perspective, note these statistics from a recent *Wall Street Journal* article: Foxconn currently employs 1 million workers in China and has at times operated as many as 100 production lines around the clock at its plant in Zhengzhou. The company has approximately 300,000 workers at the Zhengzhou facility, which is dedicated to making the iPhone5s.[3]

According to the Bloomberg report, the Harrisburg plant is part of Foxconn's strategy to move more manufacturing to the U.S. as demand increases for domestic products. Bloomberg quoted Foxconn chairman Terry Gou as saying the company wants to be part of the manufacturing "renaissance" in the U.S.

[2]http://www.bloomberg.com/news/2013-11-21/iphone-maker-foxconn-said-to-plan-investment in-pennsylvania.html

[3]http://blogs.wsj.com/digits/2013/11/27/iphone-5s-wait-time-drops-as-foxconn-boosts-production/

– Jenny Donelan

president's corner

Innovation and SID

by Brian Berkeley
President, Society for Information Display

Greetings to all of our members and readers around the world! As we look back at 2013, I observe that the display industry and academia continued to innovate at a torrid pace. This year alone, we saw full-HD resolution displays with very high (> 400 ppi) pixel densities shipped in smartphones, first commercial shipments of full-high-definition large-sized OLED television, first ultra-definition (UD, UHD, or 4K × 2K) TV screens reaching mass commercial availability, impressive flexible displays including the first mass-produced product based on a flexible display (the Galaxy Round), first mass production of OLED panels based on green phosphorescent material, extended color gamut for LCD TVs achieved by the use of quantum materials entering mainstream production, and significant improvements in touch and interactive technologies. It is truly a great time to be associated with the display industry. We can expect even more innovation in 2014.

Your involvement with SID is key to this ongoing progress. For example, by reading this magazine, and by watching SID's members-only webinars, attending chapter events, and attending SID's annual Display Week conference, we can all keep current with the rapidly emerging developments in displays, and also with related areas including touch and human interactivity.

To help SID keep up with the rapid pace of innovation and to better serve our members, authors, and supporters, SID's Executive Committee has been very busy driving continuous improvements in all elements of the society's activities, publications, and operations. In many ways, the Society is undergoing as much innovation as the display field itself. I'd like to share some of these developments with you, our members, who are the most important part of SID. If you are not yet a member of SID, I urge you to consider SID membership. While it is not possible to mention everything in limited space, I hope the following examples will provide a sense of the work in progress so that SID can better serve its membership and the display industry as a whole.

Hopefully by now, you've taken note of the upgraded content of this magazine, *Information Display*. Article quality and relevance have increased, articles covering applications have been added, and new areas such as the current series on venture capital give greater breadth and perspective to all readers. Extensive efforts are being made on SID's other publications as well, notably including our professional journal, the *Journal of the Society for Information Display* (*JSID*). A few years ago, *JSID* achieved listing in the Science Citations Index, or SCI extended list (SCIe) of professional journals. While this was a significant achievement, the SID Executive Committee has set a goal of moving *JSID* from SCIe to pure SCI status, as publication in a pure SCI journal is important for many authors and professors. *JSID*'s new editor has been focusing on continually upgrading paper quality, while also taking necessary administrative steps to ensure proper reporting of *JSID* paper citations. We believe that *JSID* and its editorial board are well down the path of increasing *JSID*'s impact factor, which is the main criterion to achieve pure SCI journal status. We hope to achieve full SCI status for *JSID* within 2 years. We have also provided better electronic access to all publications from *JSID* and the *SID Symposium Digest*, and from many other SID-sponsored conferences as well. We have seen rapid growth in online readership, which is a very encouraging sign.

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On the Frontlines of Innovation: Inspiration for "Skin-Like" Displays

by Jason Heikenfeld

I love reading *Information Display* because I can conveniently get the industry and commercial information that I will never find by reading technical articles alone. However, in the longer term, our future will be determined by emerging technologies for which even a blueprint for pilot manufacturing does not yet exist. Our society, and the mature display industry, must continue to advance new technology and applications to keep our R&D engines churning out new products and to avoid a purely commoditized and low-profit industry. Fortunately, plenty of challenges and opportunities remain.

I will argue that one of the biggest of these challenges is to make displays ubiquitous. Your immediate reaction is likely that displays are already ubiquitous. However, that could not be farther from the truth, as nearly all commercial displays are rigid and fixed in form factor. When we have a display, nearly always it is part of a device itself, and the presence of the device is obvious. When displays become ubiquitous, you will not need to reach into your pocket to pull it out; it will always and already be where you need it, and when you are not using it, you will not even know it is there.

There are some innovative attempts to arrive at this state of ubiquity, such as Google Glass, but optics imposes significant challenges for increasing the performance and ergonomics of near-to-eye displays. So what other options exist? Well, a significant leap toward ubiquity will be made as soon as color video displays become foldable or even wearable and stretchy. The concept of a rollable display has been tantalizingly close to commercialization; recall the former Polymer Vision and its attempt with its Readius product. At that time, lack of color and video made the advantages of a large display you could fold up and store in your pocket seem antiquated compared to the then new large-screen-only iPhone. In another example, Kent Displays has shown for some time now the capability to make thermo-formed displays that conform to even compound curvatures, but once these are set into their final geometry they are completely rigid.

So,where do we go from here? Well, one of the goals of this issue of *Information Display* is to stretch our imagination as a community. This issue is more than just ideas or concepts. We have assembled a list of authors deeply involved in the type of sciences and fundamental engineering breakthroughs that will ultimately lead toward our capability of creating flexible even conformal displays. The Someya group at the University of Tokyo has contributed an article titled "Imperceptible Electronic Skin," which includes sophisticated integration of both sensory and display technology. In addition, an article from the Pei Group at UCLA teaches us how to create organic LED displays that stretch much like skin. Finally, we have a contribution from the Hanlon Research Group at the Marine Biology Laboratory in Woods Hole, Massachusetts, one of the top international research groups when it comes to understanding displays in nature. This third contribution, while not electronic, shows how nature achieves performance levels in the skin of cuttlefish, squid, and other animals that even our best laboratory demonstrations fall well short of. Collectively, these articles offer key pieces of the puzzle, for both emissive and reflective displays, when it comes to commercialization of conformal and stretchable or skin-like displays.

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Dynamic Displays in Nature

Squid, cuttlefish, and octopus developed elaborate skin displays millions of years ago, with performance that is still superior in many ways to today's leading display technologies. Studying the mechanisms by which animals rapidly and efficiently change their coloration and patterning using only ambient light can offer bio-inspired routes to improved display technologies.

by Lydia M. Mäthger and Roger T. Hanlon

OVER millions of years of evolution, a small subset of animals has developed the ability to change color and pattern for camouflage and communication. The best known are probably chameleons and cephalopods (squid, cuttlefish, and octopus, as shown in Fig. 1) although lesser known examples include certain fish and amphibians. Cephalopods are by far the most versatile and can change in as little as a quarter of a second. While the majority of animals communicate through various forms of body language, as well as verbal and/or non-verbal (acoustic) signals, cephalopods have surpassed other animals in terms of developing a form of skin "display" that they can use to communicate specific messages. And, of course, their camouflage abilities are legendary.

Lydia M Mäthger *is Assistant Research Scientist at the Marine Biological Laboratory located in Woods Hole, Massachusetts. She has studied the mechanisms and functions of camouflage and communication in animals, specifically, the physics and biology of coloration and patterning, for 15 years. She can be reached at lmathger@mbl.edu.* ***Roger T. Hanlon*** *is Director of the Program in Sensory Physiology and Behavior at the Marine Biological Laboratory at Woods Hole. He holds professorships at Brown University and Rice University and his laboratory has studied rapid adaptive coloration in marine animals for 30 years.*

Lately, biologists and engineers alike have been particularly interested in the mechanisms underlying color and pattern changes in cephalopods because the structures involved are so effective at creating and mixing multiple colors – all using ambient light. Over the past 2 decades, engineers have been developing and improving various aspects of display technology (*e.g.*, e-Paper, flexible, or conformal displays) with the goal of making devices that can be used in any lighting environment and even in complex geometries like those required for wearable displays. Thus far, in comparison with the color and pattern changes of cephalopods, the display technologies lag behind in optical performance, especially in color generation.[1] Furthermore, at best, displays today are flexible, which is still a far-cry from the stretchable/conformal nature of displays in nature. In this article, we describe the optical structures and the physical mechanisms that make cephalopod color and pattern changes possible, with an attempt to identify some areas that engineers working on research and development aspects in the display industry may want to look to for inspiration.

Cephalopod Display "Materials"

In cephalopods, color and patterns are created by the action of millions of chromatophores, which are small pigmented organs (grouped into 2–3 color classes depending on the cephalopod species – red, yellow/orange, and brown/black) and structural reflector cells.[2] A cephalopod chromatophore consists of a pigment-containing sac that has dozens of radial muscle cells attached around its periphery [Fig. 2(a)]. The chromatophore muscle cells are controlled directly from the brain (not local stimuli), and through contraction and relaxation of these muscles, the pigment sac increases or decreases in area in less than 1 sec. This unusual mechanism of colorant transposition could be amenable to some materials science applications.

A key feature of adaptive coloration in animals is the refined interplay between pigments and reflectors. In addition to the pigmented chromatophores, cephalopods have iridescent reflectors termed iridophores in many parts of the body [Fig. 2(b)], and these cells have precise arrangements that may perform specific behavioral functions. (An iridescent structure can be described as having a rainbow-like appearance.) Iridophores are colorless cells that vary in size but are generally smaller than 1 mm.[3] They contain stacks of thin plates that reflect light by thin-film interference. Multilayer (Bragg) reflectors have well-defined optical features, the most obvious of which is their angle dependence. The more oblique the angle of incidence, the shorter the peak wavelengths of the reflected light. Furthermore, at around Brewster's angle, the reflected light is maximally polarized, an interesting property that may have behavioral functions because cephalopods have the ability to see polarized light. It has been

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speculated that cephalopods could even communicate this way as a form of "hidden" communication channel (since many vertebrates, *i.e.*, potential predators, lack the ability to see polarized light). This "communication" based on polarization may be of interest to display practitioners, especially those working in 3D displays that rely upon polarized light.

It is now known that some squid have the rather sophisticated ability to spectrally tune their iridescence and even switch it off completely. In *Loligo* squid, some iridescence is

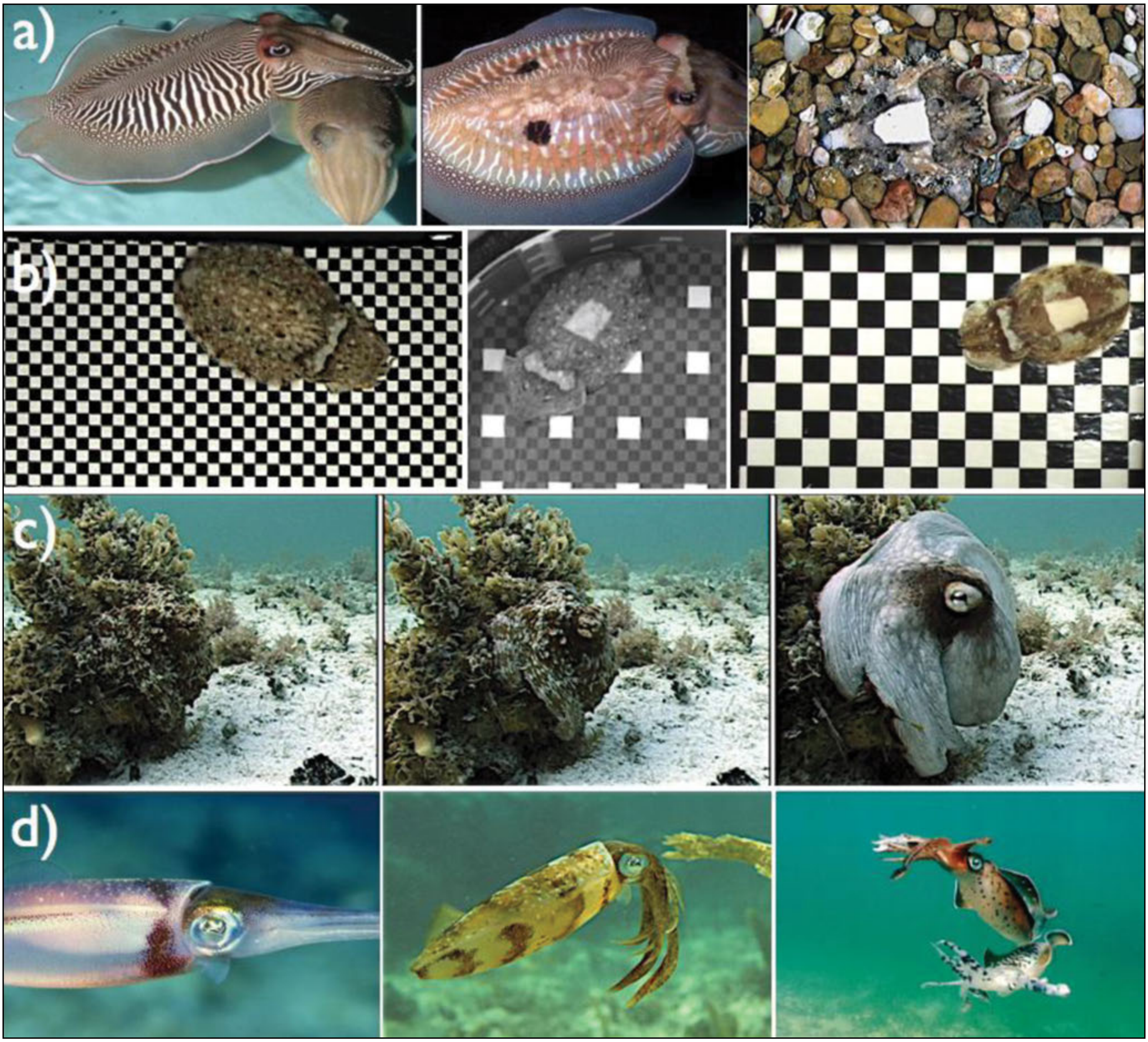

Fig. 1: *Examples of skin displays for communication and camouflage in cephalopods include: (a) from left to right, cuttlefish in a zebra pattern, a "deimatic" or threatening pattern with false eye spots, and a camouflaged disruptive pattern; (b) cuttlefish on artificial checkerboard substrates showing high-contrast patterns whose spatial frequencies match those of the backgrounds; (c) an octopus in camouflage showing a rapid transition (a total of 2 sec from left to right) to signaling as the photographer approaches it more closely (in this example, the signal is a threat display, in which the animal makes itself conspicuous with the intention of intimidating a potential predator); and (d) squid showing a "pied" signaling pattern, a camouflaged disruptive pattern, and a fighting pattern. Photographs courtesy R. Hanlon.*

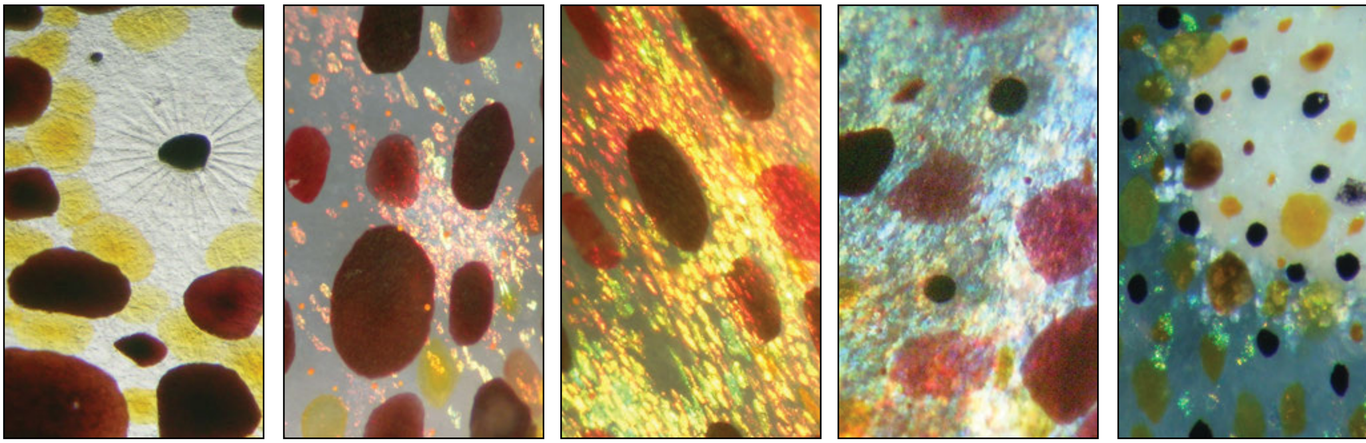

Fig. 2: Chromatophores, iridophores (iridescent reflectors), and leucophores (spherical scatterers) are responsible for color and pattern change in cephalopods. Image (a) shows brown, yellow, and red chromatophores in the squid Doryteuthis pealeii*. Located above the center of the image is a partially retracted brown chromatophore, with muscle cells clearly visible. These muscles are responsible for expanding the chromatophore pigment to full size. For scale, a fully expanded squid chromatophore (*e.g.*, bottom right of image a, but also images b, c, and d) measures about 1–2 mm in diameter; a retracted chromatophore (*e.g.*, small dark punctate structure above/left of the large expanded one) measures less than a tenth of a millimeter. In (b), iridophores (the smaller patches of red, pink, yellow, and green) appear underneath the brown and red chromatophores. Shown in (c) and (d) are examples of how chromatophores filter light reflected from iridophores. A red chromatophore at the right side of image (c) can be seen to give the reflected yellow iridescence a red hue. A red chromatophore toward the right of image (d) turns the underlying blue iridescence into purple. A similar effect can be seen in the other color classes of chromatophores. Shown in (e) is a closeup of part of a white fin spot in the cuttlefish* Sepia officinalis*. The fin spots are made up of leucophores and iridophores. Some iridophores around the periphery can be seen to reflect green light. Above the fin spot are pigmented chromatophores. For scale, the fully expanded chromatophores measure about 1 mm in diameter. Photographs courtesy L Mäthger.*

shown strongly during fighting encounters between animals and completely switched off at other times. In contrast to chromatophores, which can change within a fraction of a second, iridophore reflectance changes take longer, *e.g.*, several seconds to minutes. In some squid, the reflected wavelengths can shift by over 100 nm, *e.g.*, from infrared to red to orange, but also in other parts of the spectrum. Knowledge of exactly how these wavelength changes are generated is still patchy. The plates of squid iridophores are made up of proteins called reflectins.[4] One explanation of the observed changes in reflectance is that the protein state changes, affecting refractive index, to first enable the cell to reflect light (this would be the "on/off switch"). Secondly, with higher levels of stimulation (*e.g.*, applying the neurotransmitter acetylcholine that drives these changes), there is a change in the thickness of plates, which causes a spectral change. Essentially, one could consider this as chemically tuned color.

Kramer *et al*.[5] showed that reflectin proteins have remarkable self-assembling properties and that they can be processed into thin films, photonic grating structures, and fibers. Subsequent results show that tyrosine phosphorylation of reflectin proteins is involved in the regulation of iridescence in squid.[6] Tao *et al*.[7] studied recombinant reflectin and showed that protein assembly can be triggered by chemically stimulating the cells and that reflectin protein assembly is reversible and tunable.

These properties and operations should provide a valuable background for creating a similar type of system for optical engineering. The applicable value of such a tunable device for the military, *etc.*, may be substantial (see, *e.g.*, a recent paper by Phan *et al*.[8]). These shifts of reflectance peaks are directly relevant to display technologies that also shift optical interference, for example, P-Ink by Opalux and mirasol by Qualcomm, and are more loosely related to switchable Bragg reflectors that underpin the cholesteric displays developed by Kent Displays and Fujitsu.

An interactive way in which cephalopods change color is by filtering the iridescence through the pigmented chromatophores [Figs. 2(c) and 2(d)]. This effect can be immediate because chromatophores can be activated in a matter of milliseconds. By selective expansion, chromatophores can either change the reflected spectrum of the iridescence, create contrast against which iridescence is viewed, or block it altogether. Iridophores can also enhance the chromatophores' appearance. In squid, three classes of chromatophores (yellow, red, and brown pigments), combined with dynamically changeable iridophores, can produce colors that encompass the entire visible spectrum, enabling a wide range of skin colors. It appears that nature has once again perfected an approach that we are just now trying to implement commercially; namely, multilayered reflective displays that rely on subtractive color such as those in development by Ricoh (electrochromic) and Hewlett-Packard (electrokinetic).

Another type of structural reflector that was originally described only for cuttlefish and octopus is the white-scattering leucophore [Fig. 2(e)]. A study published earlier this year[9] shows that leucophores are cells that contain thousands of spherical microparticles called leucosomes that consist of sulfated glycoproteins or proteoglycans and reflectin. The leucophore whiteness is produced by incoherent scattering based upon a randomly ordered system. Leucophores are soft and compliant, and this system may in the future provide an interesting template for approaches to efficient light scattering in materials science and optical engineering. While the cuttlefish system is an entirely passive light diffuser, recently a tunable version has been described in squid.[10] Display engineers developing stretchable displays that require reflectors or diffusers may consider the construction and physics that nature has developed for the white-scattering leucophores.

How does the integrated system of pigments and reflectors work? A glance at Fig. 3 may help the display-industry reader appreciate the way these structures interact with light. The skin of cephalopods is layered so that each of the structures interacts with the incident and/or reflected light in some way. Generally (as with anything in nature, there are some exceptions!), we can say that the pigmented chromatophores are the most superficial structures. Beneath the chromatophores are the structural reflectors such as iridophores, while the white-scattering leucophores are generally found in the deepest layer.

Figure 3 illustrates three sample ray traces (1, 2, 3) incident on the skin. The top panel (a) and the bottom panel (b) are the same, except that the chromatophore diameters are different in each, depicting how the natural system works. Ray trace (1a) shows a ray of white light incident on an iridophore cell. Due to constructive interference, the reflected light is blue, given the periodic spacing of the plates in that iridophore. Ray trace (1b) shows that when the brown chromatophore expands, it absorbs most of the reflected blue light. Ray trace (2a) shows diffusely reflected white light from a leucophore, which in (2b) is red because it first passes through the expanded red chromatophore. Ray trace (3a) depicts incident light filtered by a yellow chromatophore and then reflected from an iridophore with a plate spacing shifted closer to the red spectrum such that the reflected light is orange. Ray trace (3b) shows the same yellow-filtered light appearing greenish because the iridophore plate spacing decreased and caused a wavelength shift toward the shorter end of the visible spectrum. These are just a few examples of how chromatophores, iridophores, and leucophores interact to produce a wide range of visual effects.

It is interesting to note that these animals are able to "interconnect" all these optical layers, switch them independently, and do so such that their peripheral interconnects (nerves, supply of nutrients, *etc.*) have almost no optical loss or influence on the reflected color. Today's best display technologies are nowhere near this level of optical transparency for interconnects, let alone also making them flexible or conformal/stretchable.

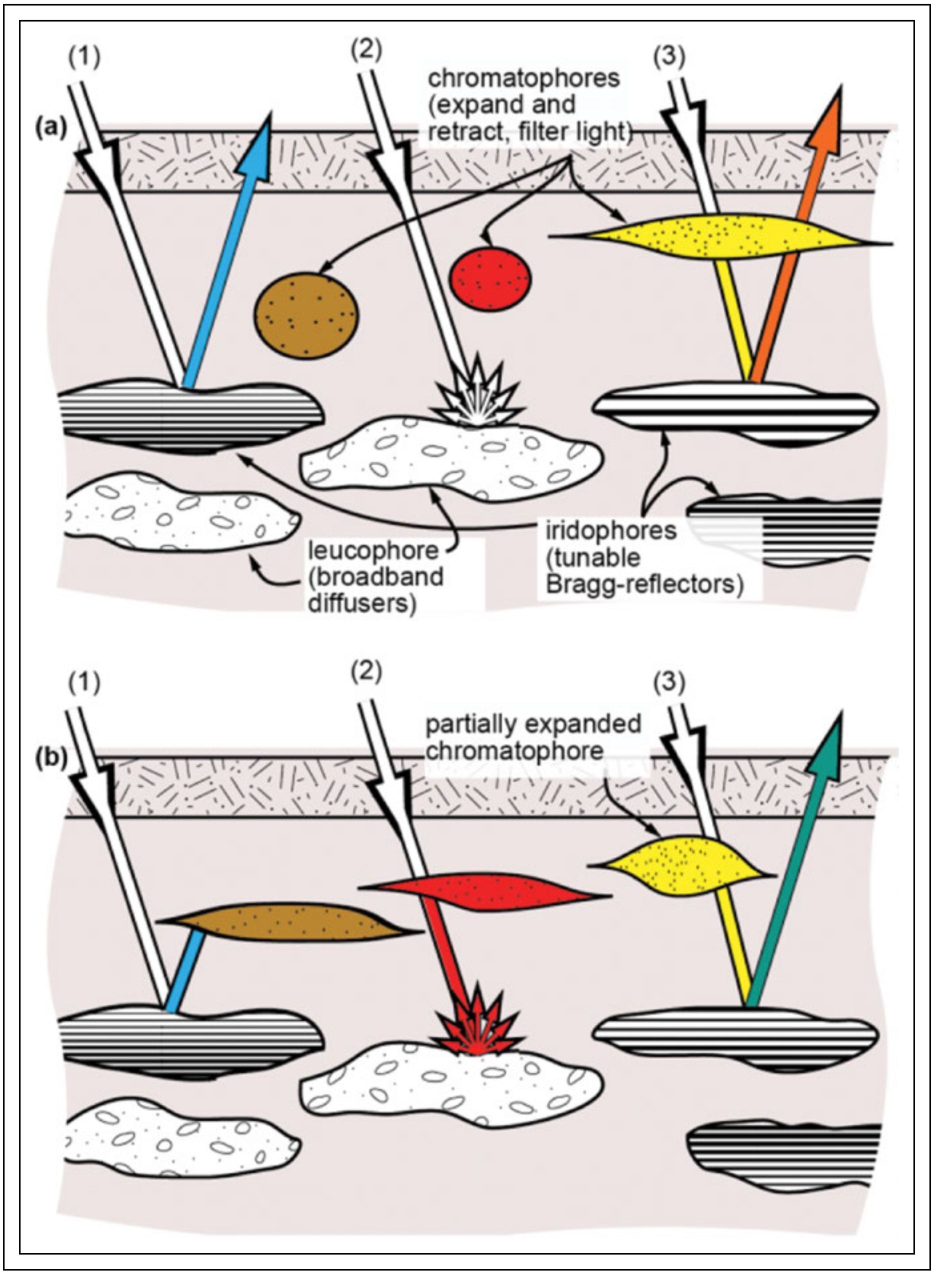

Fig. 3: *This diagram of cephalopod skin shows how the three main skin structures – chromatophores, iridophores, and leucophores – interact to produce a range of visual effects. Shown are two example states (a,b) and three distinct ray traces (1, 2, 3). After Kreit* et al.[1]

Biophotonic Systems as a Source for Advances in Displays

In terms of the use for active display in nature, cephalopods change skin color and pattern not only for adaptive coloration (*i.e.*, camouflage) but also for communicative purposes, such as to attract mates and deter rivals or to dazzle potential prey and confuse a possible predator. Communicative signals can be elaborate and colorful. Most of the time, they involve high-contrast visual effects (see Fig. 1). For example, the "zebra" display shown by cuttlefish males during courtship is produced by maximally expanding the dark chromatophores in specific areas to achieve a dark striped pattern and by retracting the chromatophores in between, thereby exposing the bright white leucophores underneath. In another example of a high-contrasting pattern, a set of "false eyespots" is displayed. These are intended to startle an approaching predator. Many cephalopod species have dozens of pattern variations to choose from in order to communicate and camouflage effectively in their habitat.

In addition to the colors and patterns created by the skin, various body postures are used to enhance the visual effect, making the adaptive and communicative patterns even more effective. While cephalopods are restricted in the way in which they use their skin structures for camouflage and communication – the patterns are pre-set in specific ways and the system cannot produce an infinite number of patterns – it is certainly possible that this kind of biophotonic system could produce a very large number of patterns if adapted appropriately. Modern displays adjust to their environment typically only in terms of brightness. The algorithms that animals utilize could be exploited by display engineers to find optimal ways to adjust patterns, background intensities, and other factors to maximize the ability to communicate information clearly to the user. Animal adaptive coloration provides excellent inspiration, as animals often select a non-obvious choice of pattern display, which achieves the desired end-result with minimal "display resolution."

We have seen that there are many similarities in the way that cephalopods have mastered the challenges of creating effective displays and the way that engineers are seeking to solve the same types of problems. Both use pigments that are spread out or compacted to achieve a visible effect. Cephalopods use muscle fibers; in electronics, electric fields do the trick. However, nature has had a long head start in creating an efficient and sophisticated solution, and there are still things we can learn from studying this natural system. Foremost among these is that cephalopod color and pattern changes make use of ambient light. The animal's skin reflects, transmits, absorbs, and scatters light in specific ways (some structures even fluoresce) to achieve an optical effect. In this regard, cephalopods are more efficient than electronic devices because the latter generally require electric power to generate emissive light, whereas the structures in cephalopods (once developed) need energy only to enable change – the color production itself requires no energy at all. A natural feature that we may particularly learn from is that in cephalopods the final skin "display" is the result of the optical interaction between a number of different structures (pigmentary and structural). To date, we do not fully understand how these structures interact to produce the final appearance of the animal, but the fact that pigments and structural reflectors are used together (and many animals do this, not just those that can change color and pattern) seems to indicate that there is a fundamental mechanism worth paying attention to.

Another notable feature of cephalopod skin is the flexibility with which the animals can create three dimensionally textured surfaces. Particularly cuttlefish and octopus can selectively wrinkle and fold their skin (the intention of this is to be able to camouflage next to textured objects when the need arises). How these animals accomplish this may be of particular interest to researchers and engineers working on display technologies that require surface texture.

Perhaps it is worth quoting the saying placed over the library entrance door in the 1890s at the Marine Biological Laboratory: "Study nature, not books." Nature provides a deep repository of elaborate biophotonic systems, and many, if not most, of these remain unexplored. Whether our research is in the generation of color and pattern for displays, textured surfaces, or flexible displays that can be stretched and rolled, cephalopods, fish and some terrestrial color changing animals may still be able to show us a few tricks along the way.

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Photo courtesy of Timothy Hursley

Plaza art outside the San Diego Convention Center frontline technology

Intrinsically Elastomeric Polymer Light-Emitting Devices

Imagine an electronic display nearly as transparent as a window, or a curtain that illuminates a room, or a smartphone screen that doubles in size stretching like rubber. A recent demonstration of intrinsically elastomeric light-emitting devices suggests that such examples may soon become viable.

by Jiajie Liang and Qibing Pei

STRETCHABLE or ultra-flexible electronics and optoelectronics have emerged as alternative technologies for the next generation of electronic applications. These elastomeric light-emitting display and solid-state lighting systems are fabricated on substrates that can be stretched, twisted, and folded – they are often referred to as skin-like displays.[1] Companies such as Samsung, LG, and Sony have recently demonstrated prototypes of flexible displays and TV sets based on organic light-emitting diodes (OLEDs). However, true stretchability is much more demanding than flexibility.

While flexible displays normally need to withstand strains of no more than 1%, skin-like displays must be able to endure strains or shape changes of over 10%.[2] The realization of stretchable displays would not only permit significantly more durable and even unbreakable devices to be created, it would also enable more exotic applications such as expandable and foldable screens for smartphones, electronic clothing, rollable or collapsible wallpaper-like lamps and curtains, bio-compatible light sources for *in vivo* or epidermal medical devices, and electronic skin in robotics.[3–5]

To fabricate stretchable or skin-like electronics, it is important to make the devices mechanically compliant and capable of stretching without undergoing physical damage.[2] Strategies employing elastic interconnects and buckled or wavy materials that are otherwise unstretchable have been reported to fabricate stretchable semiconductor devices and displays.[6–8]

An alternative approach to realizing stretchable displays has been developed by a research group with the Department of Materials Science and Engineering at UCLA. This approach is based on a radically different strategy, whereby only elastomeric materials are employed to fabricate skin-like polymer OLEDs (PLEDs).[1] An external deformation of the PLEDs causes more or less the same amount of strain in all constituent materials, including the electrodes, light-emitting semiconductor, and substrate. One of the major obstacles to fabricating skin-like PLEDs and displays had been the lack of an elastic transparent electrode that combines high visual transparency, good surface electrical conductivity, high stretchability, and high surface smoothness. These are all features essential to the fabrication of stretchable OLEDs.

Indium tin oxide (ITO) has been the ubiquitous transparent conductive electrode (TCE) material for practically all forms of displays. However, ITO routinely cracks under an applied strain of ~1%, limiting its application in flexible and stretchable optoelectronics.[9] Several alternative materials, including carbon nanotubes (CNTs), graphene, and conducting polymers, have been investigated to replace ITO to make a stretchable TCE with varied success.[10–12] These carbon- or polymer-based materials have relatively low electrical conductivity, and the sheet resistances of corresponding TCE are 1–2 orders of magnitude higher than that of ITO, making them unsuitable for OLEDs and organic solar cells. These materials also incur relatively high production costs.

Recently, percolation networks of metallic nanowires, such as silver nanowires, have shown promise in rivaling ITO in sheet resistance and visual transparency.[13,14] In addition, the mechanical compliance of silver-nanowire percolation networks could potentially be exploited as flexible and stretchable electrodes.[15] However, silver-nanowire films coated

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directly on substrates have two critical drawbacks: surface height variations observed to be greater than 100 nm and weak bonding between the silver-nanowire networks and substrate such that mechanical scratches or repeated deformation could cause detachment of the silver nanowires and device failure. Cumbersome techniques, such as introducing polymer overcoating or hot-pressing, could alleviate these issues, but, in turn, introduce new issues such as reduced uniformity due to inadvertent removal of coating materials in some areas.

The research team at UCLA has developed a solution in the form of a transparent composite electrode comprising a thin percolation network of silver nanowires laid in the surface layer of rubber.[1,16–18] This composite electrode meets all the requirements for the fabrication of high-performance OLEDs.[19] The elastomeric OLEDs employ a pair of transparent composite electrodes sandwiching an electroluminescent polymer layer that is also elastomeric.[1] The OLEDs have a maximum brightness of 2200 cd/m^2 and a luminous efficacy of 11 cd/A (total emission from both sides) that are on par with OLEDs fabricated on ITO/glass using the same emissive polymer. Moreover, the elastomeric OLEDs exhibit rubbery elasticity at room temperature, are collapsible and twistable and can still function while stretching to more than twice the original size (strains as large as 120%). This material can also survive more than 1000 repeated continuous stretching cycles at 30% strain. Small stretching actually enhances its light-emitting efficacy as a result of enhanced electron injection and thus increased balance of electron and hole injections at small strains. The fabrication process is scalable and was readily adapted for the demonstration of a simple passive-matrix monochrome display containing multiple pixels.

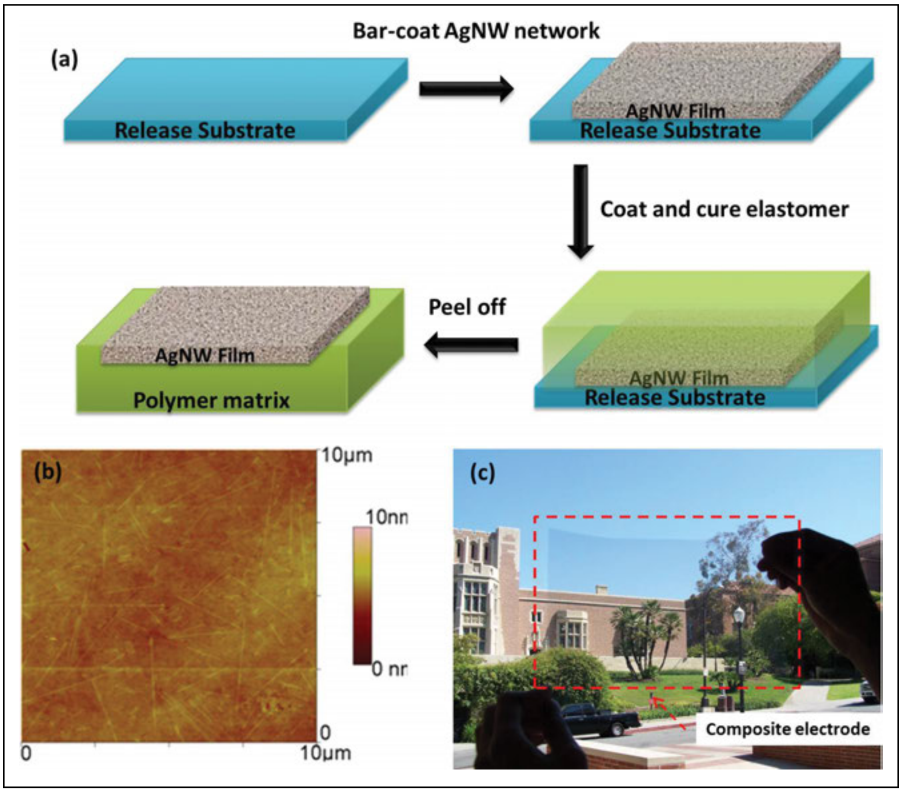

Fig. 1: At top (a) is a schematic illustration of the manufacturing process of an elastic transparent silver-nanowire-PUA composite electrode. An atomic force microscopy (AFM) topographic image of the silver-nanowire–PUA composite electrode appears in (b). And (c) is an optical image of a silver-nanowire–PUA composite electrode (25 cm × 15 cm, within the red dashed rectangle).

Stretchable Transparent Composite Electrodes

Silver nanowires with a length-to-diameter aspect ratio of approximately 500 were used to form a conductive silver-nanowire network with high electrical conductivity and mechanical compliancy. A schematic representation of the manufacturing process for stretchable silver-nanowire-based composite electrodes appears in Fig. 1(a). Basically, a dispersion of silver nanowires in isopropanol was coated on glass substrates utilizing Meyer rod or air-brush spraying. The resulting transparent conductive coating on release substrates (glass or PET) was then overcoated with a precursor solution comprising a siliconized urethane acrylate oligomer, an ethoxylated bisphenol A dimethacrylate, and a photo-initiator. The coatings were cured under UV and then peeled off as free-standing silver- nanowire polyurethane acrylate (PUA) composite electrodes. The resulting composite electrodes fabricated by this *in situ* substrate formation and transfer method generally had a smooth surface with roughness lower than 5 nm [Fig. 1(b)]. Due to the large aspect ratio of the silver nanowires used, with silver being the most conductive metal, a conductive percolation network was formed using an extremely low coating density of nanowires. The inter-nanowire contact resistance was reduced by thermal treatment that forged nanowire–nanowire fused joints. A low sheet resistance of 15 Ω/sq. could be obtained with a coating density of only 130-mg silver nanowires per square meter area. This all-solution-based fabrication process is scalable to produce large-area sheets [Fig. 1(c)].

The transmittances for the neat PUA matrix and silver-nanowire–PUA composite electrodes with various silver-nanowire coating densities, and thus sheet resistances are shown in Fig. 2(a). The silver-nanowire–PUA composite electrode with a resistance of 15 Ω/sq. exhibits a transmittance higher than 81% in the range of 500–1000 nm, which is comparable to those of ITO/glass and better than commercial ITO/PET electrodes.

To test the bonding force between the silver nanowires and PUA matrix, Scotch adhesive tape was applied to the conductive surface of the silver-nanowire–PUA composite electrode and peeled off. After 100 such tests, the sheet resistance of the silver-nanowire–PUA com-

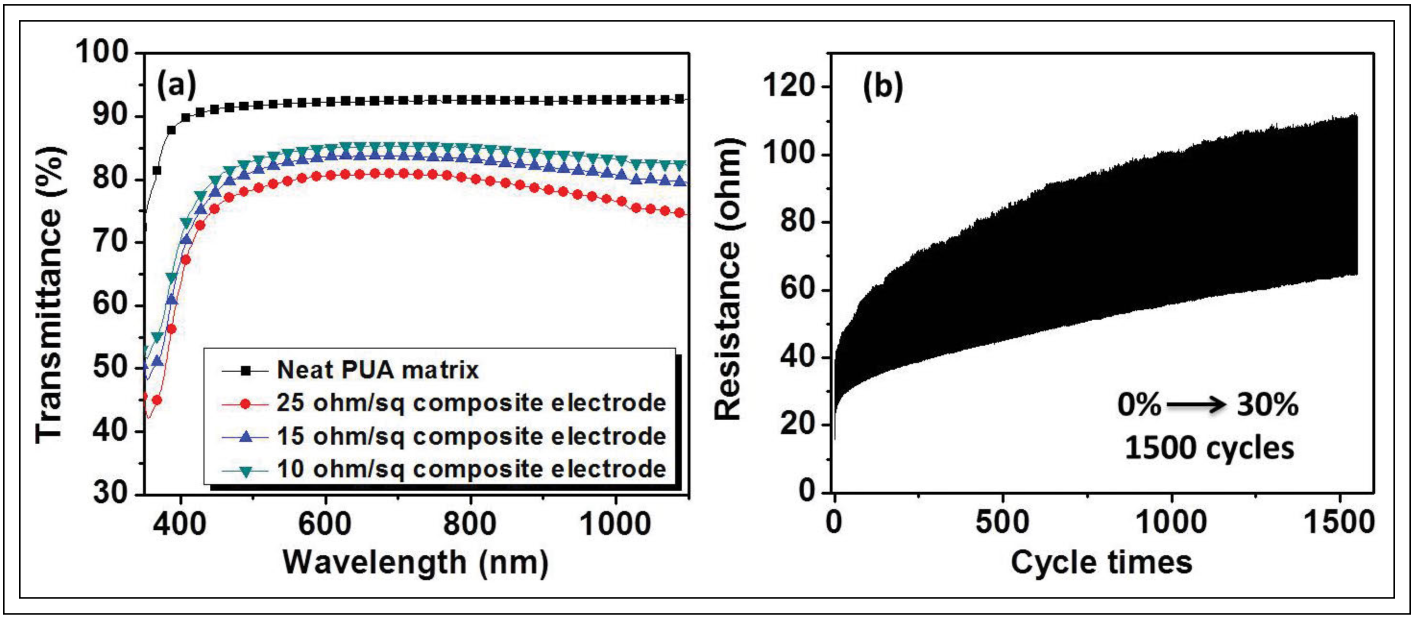

Fig. 2: At left (a) are the transmittance spectra of a neat PUA film and silver-nanowire–PUA composite films with a specified sheet resistance (thickness ~150 µm). At right (b) is a graph representing transient resistance measured during 1500 cycles of stretching-relaxing between 0% and 30% strains for a 15 Ω/sq. silver-nanowire–PUA composite electrode.

posite electrode remained unchanged, indicating good bonding force between silver nanowires and PUA. The strong bonding between the PUA elastomer matrix and silver nanowires is also beneficial in preventing long-range motion or sliding of the silver nanowires and in preserving the nanowire–nanowire junction during large-strain deformation of the composite electrodes.

The resistance evolution of silver-nanowire–PUA composite samples during continuous stretching-relaxing cycles between 0 and 30% linear strain is shown in Fig. 2(b). The baseline sheet resistance for the silver-nanowire–PUA sample only increased from 15 to 45 Ω/sq. after 1500 stretching–relaxing cycles. The sheet resistance at 30% strain also showed a gradual increase with stretching cycles and reached 85 Ω/sq. only after 1500 cycles, which is still lower than most freshly prepared transparent electrodes based on carbon nanotubes, graphene, or conducting polymers without stretching. The improvement in stretchability is possible due to the unique microstructure of the composite electrode in which the silver-nanowire percolation network is embedded within an elastomeric matrix. The latter prevents sliding or long-range drift of the nanowires.

Moreover, the composite electrodes can be stretched to as much as 100% strain while sheet resistance remains below 1 kΩ/sq. Having a smooth conductive surface is critically important for the fabrication of thin-film electronic devices such as OLEDs or polymer solar cells. This requirement has been particularly challenging for new electrode materials replacing ITO/glass. The elastomeric composite electrodes have a conductive surface that replicates the surface of the release substrates. Using glass as the release substrates, the surface roughness of the composite electrodes was found to be less than 5 nm. No cracks, voids, or buckling patterns were observable on the surface. Stretching–releasing cycles to 30% strain did not significantly increase the roughness.

Intrinsically Elastomeric PLEDs

To fabricate elastomeric PLEDs, a polymer light-emitting electrochemical cell (PLEC) architecture was employed. The PLEC was selected, instead of the conventional OLED architectures, because of the simplicity of the PLEC device structure, which does not require specific electrode work functions for charge injections.[20,21] The research group's recent work on the fabrication of high-performance and fully solution-processed PLECs by spin-coating, rod-coating, and/or blade-coating at ambient conditions advanced the fabrication of the PLECs to the point where it is compatible to a low-cost roll-to-roll process.[22] The process of fabricating elastomeric PLEC, as illustrated in Fig. 3, started with spin-coating a thin layer of poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS) on a silver-nanowire–PUA composite electrode as an anode. The thin PEDOT layer helped protect the PUA matrix from solvent attack in the subsequent coating of the electroluminescent polymer layer. The electroluminescent polymer layer consisted of a blend of a yellow light-emitting polymer (SuperYellow), ethoxylated trimethylolpropanetriacrylate (ETPTA), polyethylene oxide (PEO), and lithium trifluoromethane sulfonate (LiTf).

SuperYellow was selected for its very high molecular weight, which is suitable for large-strain stretchability. ETPTA was chosen for its capability to conduct ions and to polymerize to form a highly cross-linked polymer network that ceases to conduct ions. This property is important for the formation of a stable PIN junction.[23,24] PEO, an ionic conductor widely used for solid electrolytes, was added to enhance the stretchability of the cross-linked ETPTA network. LiTf is a widely used salt in solid electrolytes. In the PLEC, LiTf provides ionic dopants to dope

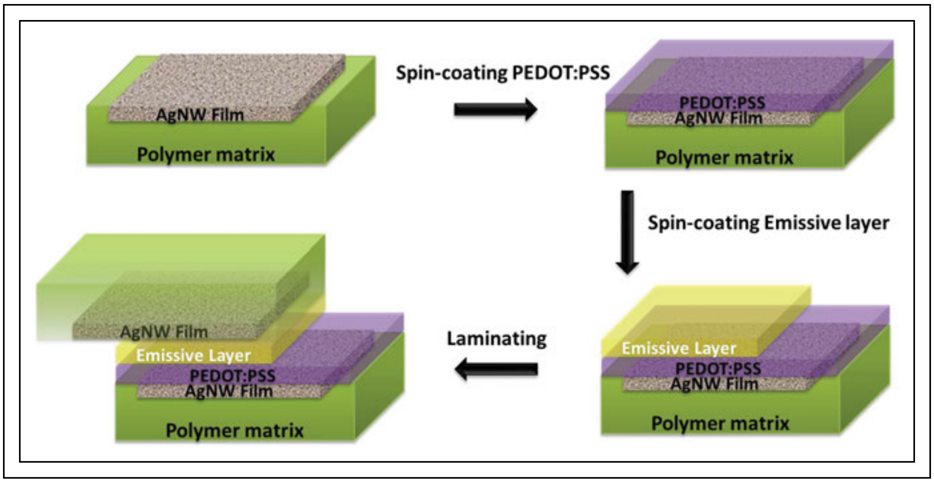

Fig. 3: This simplified rendering shows the fabricating process for a stretchable PLED device based on a pair of silver-nanowire–PUA composite electrodes (not to scale). The processes are all-solution based (AgNW = silver nanowire).

SuperYellow in the formation of a PIN junction. A second silver-nanowire–PUA composite electrode (as cathode) was stacked onto the emissive polymer layer, face down and laminated to complete the device fabrication.

The PLEC was initially driven at a constant current to establish a PIN junction in the emissive polymer layer. The pre-charged PLEC can subsequently be operated like a conventional OLED with rapid turn-on. Characteristic performance for the PLEC is presented in Fig. 4. Light emission in this device turns on at 6.8 V and reaches a peak brightness of 2200 cd/m^2 at 21V. The luminous efficacy reaches 5.7 cd/A at the maximum brightness. The driving voltage at 10, 120, and 320 cd/m^2 brightness is 9, 14, and 16 V, respectively. These voltages are in the same range as typical polymer-based OLEDs. The PLEC light-emission efficiency continuously increases with the drive voltage and brightness, which indicates unbalanced injections of electrons and holes. The injection balance is enhanced at higher current density.

Both charge-injection electrodes of the PLEC are transparent, and the emissive layer is semitransparent. The PLEC is thus semitransparent, as can be seen in Fig. 4(c). Light produced in the electroluminescent polymer layer escapes from both surfaces of the device with nearly identical luminance and efficacy. The actual maximum external current efficacy of the stretchable PLEC at the maximum brightness thus should account for emissions from both surfaces and adds up to 11.4 cd/A. The calculated external quantum efficiency is 4.0%. This performance is comparable to state-of-the-art PLEC based on SuperYellow and fabricated on ITO/glass substrate as anode and evaporated aluminum as cathode.[23,24] The device is bendable and can be folded around a 400-µm-thick piece of cardboard without causing any damage to its mechanical integrity or electrical properties [Fig. (4c)].

The PLEC device can be uniaxially stretched up to 120% strain with uniform bright emission across the entire luminous area at strains up to 120% (Fig. 5). When biased at 12 V, the PLEC shows an initial increase of brightness from 0 to 20% strain, then decreases as the strain is further increased. Interestingly, the luminous efficacy shows a 200% increase, from 1.0 cd/A before stretching to 3.0 cd/A at 40% strain. It levels off up to 80% strain and then begins to decrease, but still remains at a fairly high value of 2.1 cd/A at 120% strain, which is still 100% higher than its original value. An investigation of charge injections indicates that the increasing efficacy with strain probably results from a more balanced injection of electrons and holes when the device was under strain. The PLEC can be repeatedly stretched between 0 and 30% strain for 1000 continuous cycles. As shown in Fig. 5(c), the luminous efficacy of the PLEC drops rapidly in the first 100 cycles and then stabilize in subsequent cycles. Since 30% strain at room temperature is sufficient for most biomedical or bio-inspired

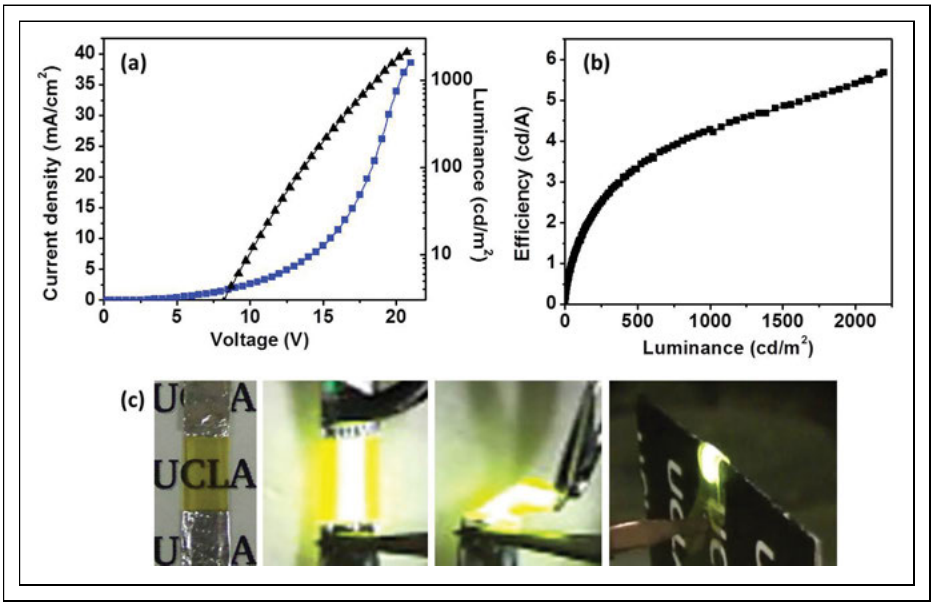

Fig. 4: At upper left (a) are shown the current-density–luminance–driving-voltage characteristics of an elastomeric PLEC device. (b) depicts the luminous-efficacy characteristics of the device. At lower left (c) are photographs of the PLEC (original emission area: 3.0 mm × 7.0 mm) unbiased, biased at 12 V, deformed to show light emission from both surfaces and folded around a piece of cardboard 400 µm thick.

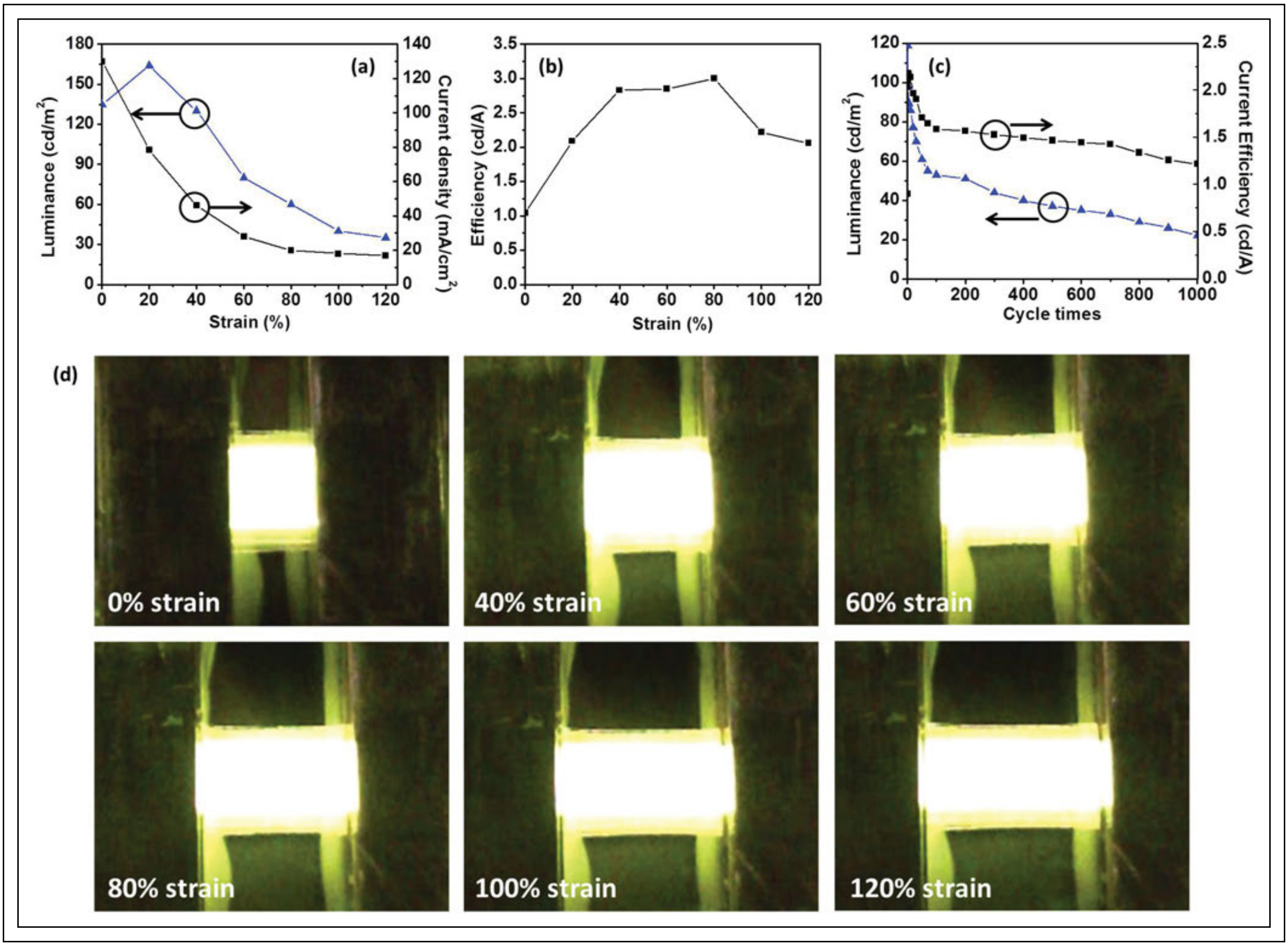

Fig. 5: The chart at upper left (a) depicts current-density and luminance characteristics of a PLEC device at 12 V with increasing strains. Chart (b) shows current-efficacy characteristics of the device with strain and chart (c) plots the luminous efficacy at 0% strain during 1000 continuous cycles of stretching–relaxing between 0 and 30% strains. In (d) are photographs of a PLEC (original emission area: 5.0 mm × 4.5 mm) biased at 14 V at specified strains.

applications, the elastomeric PLEC is a true skin-like light emitter.

OLEDs generally require hermetic sealing. Packaging is thus another important issue to address for skin-like OLEDs. The fabrication and operation of the stretchable PLECs described above were conducted in a nitrogen-protected glove box with oxygen and moisture contents both kept below 0.5 ppm. To take the devices out of the glove box, a thermally cross-linked polyurethane (TCPU) was used to sandwich the device as shown in Fig. 6(a). This encapsulated device, with uniform lighting area, could still be stretched repeatedly, stretched, and wrapped around a person's finger [Fig. 6(b)] and twisted [Fig. (6c)]. The storage lifetime of this TCPU-sealed device in air was only about 1 week. There do not appear to be any elastomeric materials capable of hermetically blocking moisture and oxygen. However, several recent and encouraging developments that may lead to the eventual development of a stretchable barrier material include elastomers incorporated with graphene[25] and layered silicate.[26]

The fabrication process of the stretchable PLEDs could be adapted to demonstrate pixelated displays. Figure 7(a) illustrates the process needed to fabricate a simple pixelated display employing the same technique described above except that the silver-nanowire-based composite anode and cathode are patterned into rows and columns and the two patterned electrodes are aligned at a 90° angle. Figure 7(b) includes optical images of an encapsulated elastomeric display consisting of 5 × 5 pixels. The display is semitransparent – the background logo can be clearly seen through it. Stretching at a 10% strain does not affect the uniform light emission of each pixel, and the pixels can be selectively addressed [Fig. 7(b)]. It is possible to pattern the silver-nanowire traces to line widths under 100 µm, and researchers are working on higher-resolution skin-like displays.

Prospects for Skin-Like OLED Displays

High-performance elastomeric OLEDs can be fabricated through a relatively simple, all-solution-based process. A key development is the elastomeric transparent composite electrodes that combine high optical transmittance, surface electrical conductivity, surface smoothness, and rubbery elasticity, all essential for the fabrication of organic thin-film electronic devices. The ability to form a light-emitting PIN junction *in situ* in the emissive polymer layer simplifies the OLED device architecture and thus allows the fabrication of the skin-like PLEDs and displays. There are plenty of opportunities to further increase the performance and stretchability.

There are still major technical challenges to be overcome before skin-like PLEDs and displays can be commercialized, such as synthesis of transparent sealing materials, synthesis of elastomeric electroluminescent polymers, an increased device lifetime to at least thousands of hours, and the development of stretchable TFTs. Once these are overcome, the skin-like PLEDs and displays will lead to a bright future where information and lighting are provided in various thin, stretchable, or conformable form factors, or are invisible when not needed. Such technologies will definitely enable a number of very exciting products along the way.

Acknowledgments

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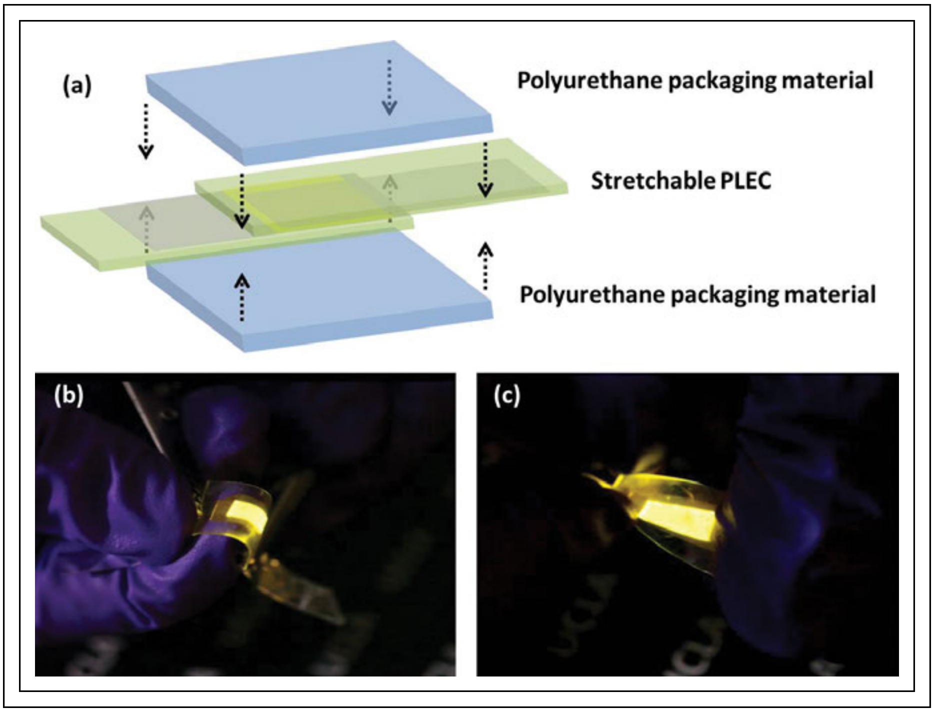

Fig. 6: At top (a) is a depiction of the lamination of an elastomeric PLEC device between two layers of a polyurethane packaging material. Below are images of an encapsulated PLEC device that is (b) stretched, bent, and wrapped around a finger and (c) formed into a twisted shape.

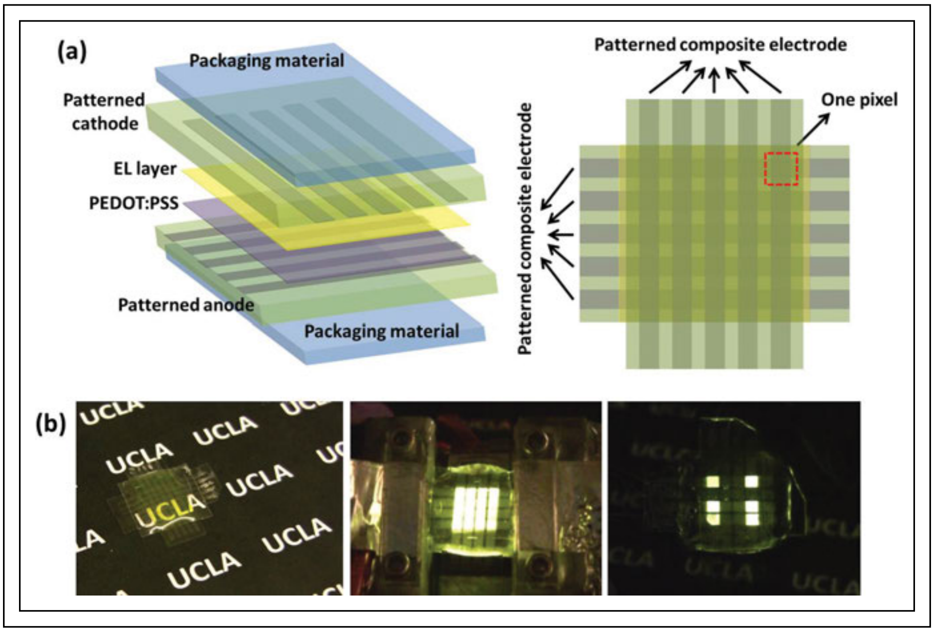

Fig. 7: A schematic illustration (a) at top left and a top-view illustration at top right depict an encapsulated elastomeric PLEC display consisting of 5 × 5 pixels. Below (b, left to right) are photographs (with UCLA logos part of the background surface) of a stretchable display unstretched with 5 × 5 pixels all turned off, stretched with all pixels turned on, and stretched with selected pixels turned on (pixel size without stretching is 1 mm × 1 mm).

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Imperceptible Electronic Skin

The authors describe recent progress, bottlenecks, and future applications for extra-light and flexible interfaces such as electronic skin.

by Tsuyoshi Sekitani, Martin Kaltenbrunner, Tomoyuki Yokota, and Takao Someya

ELECTRONIC SKIN (E-Skin) is a flexible, stretchable sensor array that can essentially computerize a surface, including that of robots and human beings. The ideal E-Skin is still under development, but it will be sensitive to heat and pressure and also be so light that a user or wearer is unaware of its presence. It will stretch and conform to a variety of surfaces, including over large areas. Such a bionic skin applied directly to the human body could be used to monitor medical conditions or to provide more sensitive and life-like prosthetics with sensing "skins."

Our research group at the University of Tokyo first developed E-Skin about a decade ago.[1,2] We wanted to create large sheets of this material and embed them with enough sensors to at least roughly mimic the abilities of human skin and to do that economically. We dreamed of making an electronic skin embedded with temperature and pressure sensors that a robot could wear, so that if a robot health aide shook hands with a human patient, its sensor-clad skin would be able to measure some of the person's vital signs at the same time. In this article, we describe recent research in terms of progress, bottlenecks, and future prospects for electronic-device–human interfaces such as E-Skin.

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Uses of E-Skin

Flexible and stretchable electronics using organic transistors could serve a wide range of biomedical applications. As just one example, we have experimented with electromyography, the monitoring and recording of the electrical activity produced by muscles. We distributed organic-transistor-based amplifiers throughout a 2-μm-thick film made of polyethylene-naphthalate or polyethylene-terephthalate, and this allowed us to detect muscle signals very close to the source, which is key to improving the signal-to-noise ratio and thus the accuracy of the measurements. This was done by attaching electrodes with adhesive gels directly to the muscle surface. Conventional electromyography techniques typically use long wires to connect sensors on the skin with amplifier circuits, causing the signal-to-noise ratio to be pretty poor.[9,10] In another example, in collaboration with the medical school at the University of Tokyo, we are working on an experiment that will place one of our amplifier matrices directly on the surface of a rat's heart. We expect that we will be able to detect electrical signals from the heart with high spatial resolution and superb signal-to-noise ratios. Another example of E-Skin used internally is a catheter with a surface integrated with electronic circuits that can measure the pressure distribution within blood vessels.

Real biological skin has the critical ability to sense many variables at once. Our early generations of E-Skin have adopted an integrated system that simultaneously detects pressure and temperature and maps those stimuli to particular locations on the skin's surface. An ultrasonic skin covering a robot's entire body could work as a 360° proximity sensor, measuring the distance between the robot and obstacles. This would prevent the robot from crashing into walls or objects and or even allow it to interact safely with our relatively soft and fragile human bodies. In a similar fashion, for humans, electronic skin could enable prosthetics or garments that are hyper-aware of their surroundings.

Requirements and Raw Materials for E-Skin

Stretchability is an important key to realizing imperceptible E-Skin. The stretchability of the human epidermis is around 20%. To create similarly stretchable electronics , the type of electronic skin that can curve around an elbow or knee requires a thin material that can flex and stretch without destroying its conductive abilities. In our lab, we have focused on making TFTs that use various types of semiconductor materials that can be deposited in thin layers, such as amorphous silicon, low-temperature polycrystalline silicon, organic semiconductors, and carbon nanotubes.

The semiconducting materials described above have varying properties and should be chosen based on application and required performance. For example, if high electronic performance is desired, carbon-nanotube semiconductors are the best choice, and if flexibility is the main goal, organic semiconductors are better than other materials because of their inherent flexibility.

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Another key challenge in realizing stretchable electronics is to simultaneously maintain electrodes with excellent electrical and mechanical characteristics. Highly conductive materials such as metals and conductive polymers are generally hard and not stretchable. In contrast, highly stretchable flexible materials such as rubber have poor electrical characteristics. Thus far, the development of stretchable electronics has been actively carried out worldwide by transferring highly conductive materials such as metals and graphene onto rubber sheets for use in stretchable interconnections and by machining metal-evaporated films into a mesh structure to make them stretchable.

After much experimentation, we have come to the conclusion that plastic films are the best for substrates. They are rugged and hold up well to mechanical strain; they cost very little and are compatible with new manufacturing processes that can produce large, flexible sheets of electronic materials – such as roll-to-roll manufacturing. To print TFTs on a plastic film like one made of polyethylene terephthalate, the processing temperature needs to be kept low enough to prevent the plastic from deforming. TFTs made with organic semiconductors can be easily printed on plastic at room temperature.

TFTs do not just allow the electronics to be flexible – they can also help E-Skin mimic the sensitivity of real human skin. There are more than 2 million pain receptors and 30,000 thermal receptors in a person's entire skin, which is equivalent to the number of pixels found in a typical high-definition television. A major obstacle for E-Skin is figuring out how this many sensors can be integrated into electronic sheets. Two-million sensors cannot be directly wired up to the driver circuits that control them because this would require cramming 2-million contact pads onto a silicon chip. (Of course, it will not usually be necessary to create a piece of E-Skin this large.)

The solution is to do exactly what display manufacturers do for controlling the transistors in their TV screens. They use wiring layouts that allow the central processing unit to send commands to the transistors attached to individual pixels on the basis of where they lie in a big conductive grid. Each pixel's address is designated by its column and row numbers, just as is done for active-matrix displays.

Developing Flexible Transistors and Their Integrated Circuits

In 2003, Sigurd Wagner of Princeton University and colleagues reported inverter circuits and transistor arrays that were stretchable by up to approximately 10% by mounting specially prepared amorphous silicon in silicone rubber and forming transistors consisting of wavy gold electrodes.[11] This is the first reported example of stretchable electronics comprising active elements to the best of our knowledge.

In 2003, we successfully fabricated high-performance organic transistors by using the low-molecular-weight organic-semiconductor pentacene for the channel and by forming polyimide gate insulating layers on plastic substrates.[3] When we systematically examined the effects of bending strain on electrical conduction properties by freely bending the organic transistors, we found that, unfortunately, the mobility increased or decreased by at least 10% upon the application of a strain of approximately only 1% depending on the bending direction.[4] It was demonstrated that changes in the channel current upon the application of strain were independent of the relationship between the current and strain directions, but resulted from an electrical conduction phenomenon unique to polycrystalline organic semiconductors. In 2005, we also found that the minimum bending radius of the transistors was 1 mm or lower when we used a neutral-strain structure on 12.5-μm-thick thin plastic substrates. This revealed that the transistor characteristics did not deteriorate upon being subjected to a large bending strain. In bending tests, the transistors were confirmed to operate even after at least 100,000 repetitions of bending.[5]

In 2005, we fabricated a high-sensitivity organic thermal sensor using the property that a positive bias current greatly changes when an organic pn-junction fabricated using the organic p-type semiconductor fluorine copper phthalocyanine and the organic n-type semiconductor perylene tetracarboxylic diimide (PTCDI) is heated. We also successfully developed a thermal-sensor sheet that can measure temperature distribution over a large area by integrating the above organic thermal-sensor cell with an organic-transistor active matrix.[2] Thus, a fused sensor that behaved similarly to human skin was realized through simultaneous flexible pressure and thermal-sensor sheets.

In 2010, we succeeded in fabricating organic-transistor-based complementary metal-oxide-semiconductor (CMOS) integrated circuits on 12.5-mm-thick plastic substrates with a drive voltage of 2 V that can maintain their electrical characteristics while being crushed.[6] In addition, we developed a neutral-strain structure using organic polymers that do not damage organic semiconductors, thus enabling the fabrication of integrated circuits that can operate without any degradation in electrical characteristics while being bent to a radius of curvature of less than 0.1 mm. An aforementioned example of an application of this technique was a catheter with a surface integrated with electronic circuits that could measure the pressure distribution within blood vessels. This was fabricated by wrapping a transistor active matrix and a piece of pressure-sensitive conductive rubber around a 1-mm-diameter medical catheter in a spiral pattern. We also integrated and arranged organic non-volatile memory arrays and organic flexible pressure sensors in a two-dimensional lattice to form a 26 × 26 active-matrix sensor pixel that can store pressure data as an image within a sheet, as reported in the journal *Science*.[7]

Also in 2010, we developed a flexible ultrasonic imaging sheet that can detect objects without contact by integrating organic ferroelectric polymers and organic transistors.[8] Ultrasound is radiated from a source, and the ultrasound reflected at the material is received by the polymeric receiving elements. By arranging the receiving elements in a two-dimensional array, not only the distance from the objects but also the shape of the objects can be obtained as three-dimensional information. We believe this particular technology could be commercially available within 10 years.

In 2013, we fabricated high-performance organic transistors and tactile sensors on an ultra-thin polymer sheet that measured 1 μm thick – thinner than a human hair and light enough to drift through the air like a feather (Fig. 1).

Even so, this material can withstand repeated bending, can be crumpled like paper, and can accommodate stretching of up to 230%. This material also works at high temperatures and in aqueous environments, meaning that it can function inside the human body.

Further Successes

In 2005, we integrated an organic-transistor active matrix with thermal and pressure sensors on a plastic film and then processed the device using a punching machine and numerical control (NC) cutter to form a net-shaped structure, realizing a stretchability of 25% (Fig. 2).

In addition, we implemented the device on the surface of a robot and successfully read out the spatial distribution of temperature and pressure. As an advantage of this method, we found that stretchable devices can be obtained by drilling holes into devices after their fabrication and that the electrical characteristics of these fabricated devices are stable because their active elements do not deform, even while they are being stretched. The applications of stretchable devices go beyond sensors and displays. In 2010, stretchable thin-film batteries were reported by Siegfried Bauer of the Johannes Kepler University of Linz in Austria and colleagues.[12]

To this point, conventional stretchable conductive materials had been given their elastic characteristics by machining highly conductive materials such as metals into a wavy or net-shaped structure.[11,19] However, these materials are essentially not stretchable. In addition, materials obtained by this approach exhibit high electrical performance but are extremely difficult to apply to large-area electronics such as displays and sensors because of their low scalability (*i.e.*, difficulties in increasing the area) due to the use of photolithography for transferring thin-film electrodes and patterning interconnections. As a result, conventional stretchable electronics had dimensions of a few tens of millimeters at most.

In 2008, we successfully developed intrinsically stretchable conductors that can be stretched similarly to rubber [Figs. 3(a) and 3(b)] and fabricated the world's first stretchable large-area electronics using stretchable conductors as electrodes [(Fig. 3(c)].

By applying a material-process method, we succeeded in uniformly dispersing nanotube gels within rubber materials . Although the stretchability and conductivity depended on the volume ratio of the nanotubes to rubber, we realized a new stretchable conductive material that exceeded a conductivity of

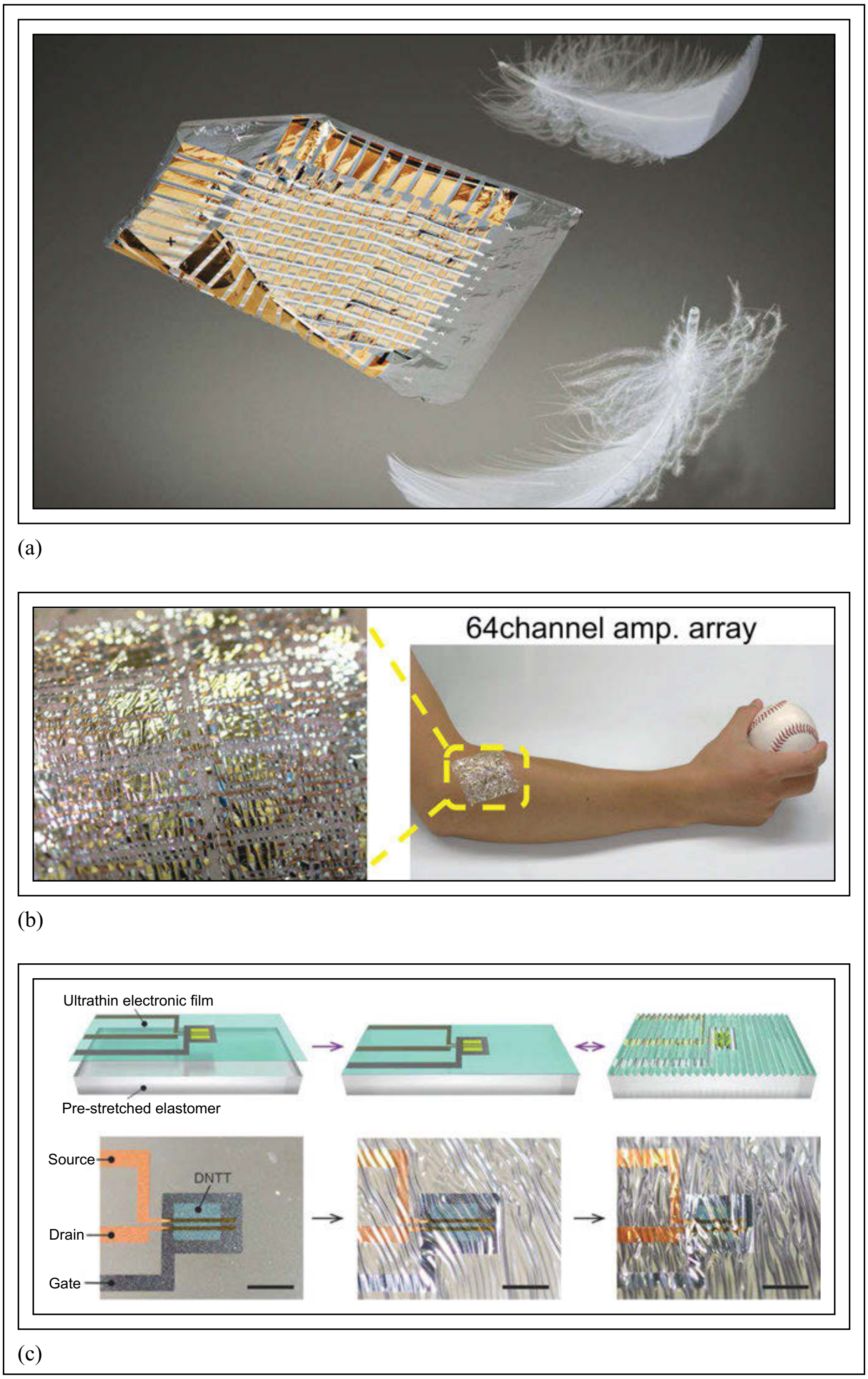


Fig. 1: *(a) A 1-μm-thick organic electronic system in which organic transistors and tactile sensors were fabricated on an ultra-thin polymer sheet light enough to drift through the air like a feather. (b) A 64-channel organic active-matrix amplifier array can be placed on the human body for imperceptible electromyogram monitoring. (c) Shown is a rendering of the manufacturing flow of a stretchable organic transistor and the corresponding photographs. Adapted from Refs. 9, 10, and 16. Copyright 2013, IEEE, and 2013, Nature Publishing Group .*

100 S/cm and had a stretchability up to 140%.[13–15] This stretchable conductor, which is in the form of a paste before drying, can be patterned by printing and applied to large-area stretchable electronics. We also succeeded in fabricating an organic-transistor active matrix that can maintain its electrical characteristics, even when stretched 70–80% by integrating the stretchable conductors and organic-transistor pixels on a rubber sheet. Furthermore, by integrating the stretchable conductors with OLED elements, a stretchable organic active-matrix LED display was realized [(Fig. 3(d)].

Parallel Progress

The next technical challenges for achieving imperceptible E-Skin that is very similar to real human skin are responsiveness, cost, environmental stability, energy management, reliability under long-term continued use, and more.[16] Here, we would like to show several approaches to further realizing electronic skin. For example, commercial pressure-sensitive rubber exhibits a maximum sensitivity of 30 g/cm^3, which is not sufficient to detect a gentle touch. To improve the E-Skin responsiveness to such stimuli, researchers are experimenting with a number of different techniques.

Zhenan Bao and her co-workers at Stanford University created a flexible membrane with extraordinarily touch sensitivity by using a type of precisely molded pressure-sensitive rubber sandwiched between electrodes.[17] The thin rubber layer has a novel design that uses micrometer-sized pyramid-like structures that expand when compressed, allowing the material to detect the weight of a fly resting on its surface. With such sensors embedded, a bionic skin could sense a breath or perhaps a gentle breeze. In the most recent application of Bao's technology, her team turned around the pressure sensors so that instead of detecting external stimuli, they measured a person's internal attributes. The researchers developed a flexible pulse monitor that responds to each subtle surge of blood through an artery. It is meant to be worn on the inner wrist under a band-aid and could be used to keep track of a patient's pulse and blood pressure.

Ali Javey and his co-workers at the University of California, Berkeley, first figured out how to make flexible, large-area electronic sheets by printing semiconducting nanowires onto pliable substrates such as plastics or paper. Then they added strain sensors to the material, which could endow their bionic skin

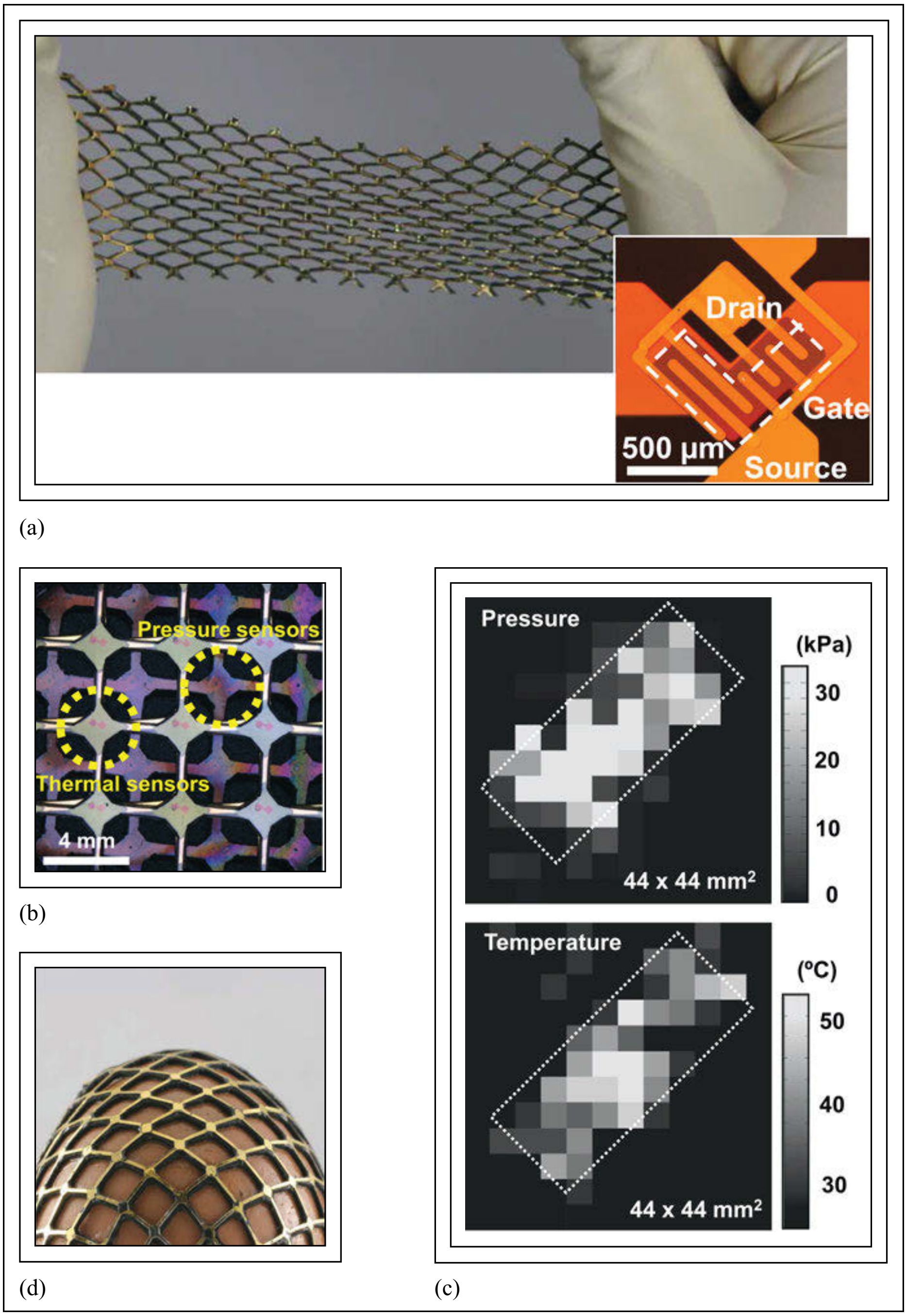


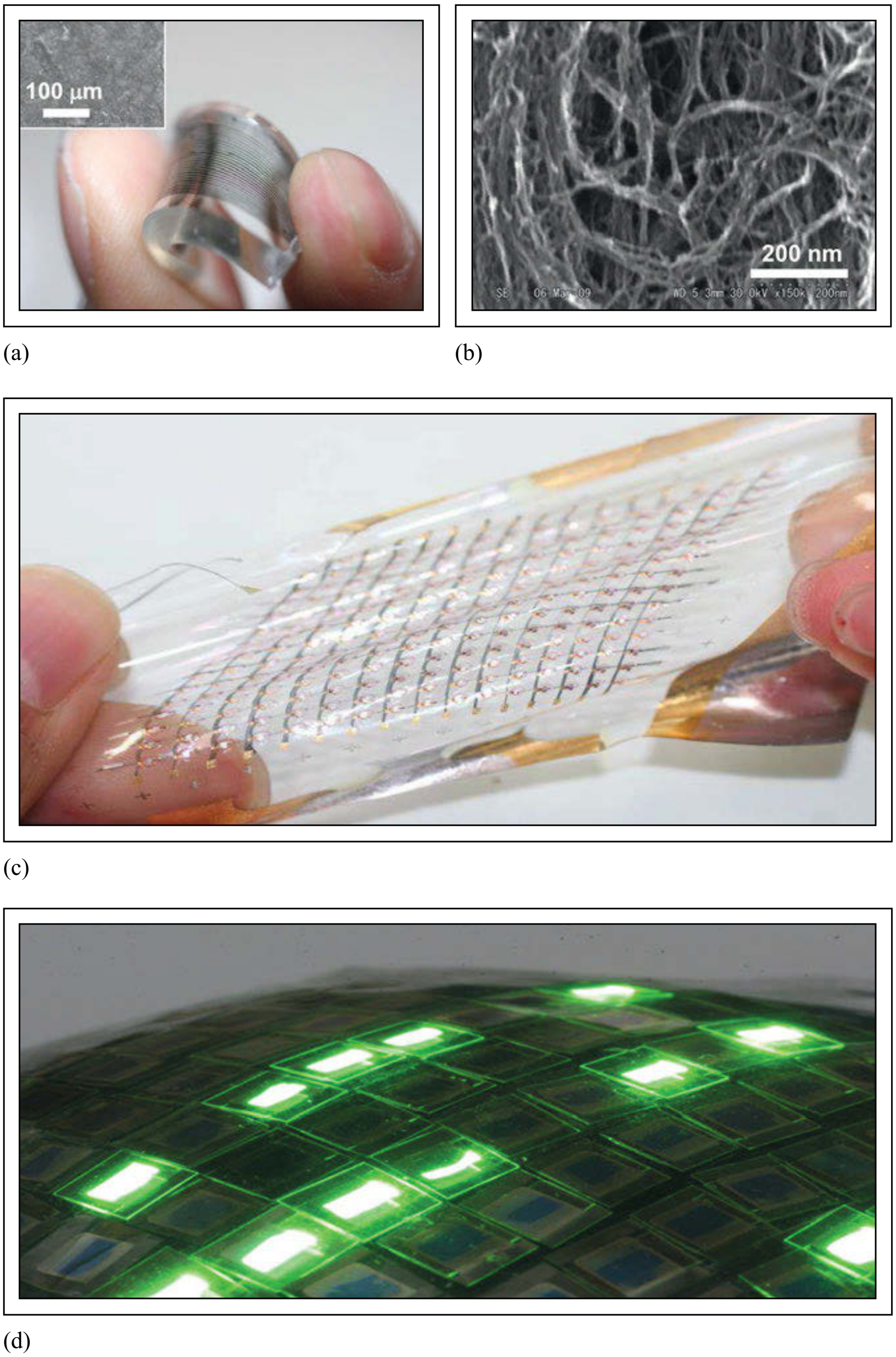
__Fig. 2:__ (a) Shown is a 25% stretched plastic film with organic transistors, pressure-sensitive rubber, and thermal sensors processed mechanically to form unique net-shaped structures and (b) its magnified picture. (c) Demonstrated is the spatial distribution of pressure and thermal information using stretchable E-Skin. The saturation current or drain-source current of organic TFTs in an active matrix is measured at various temperatures under application of pressure (30 kPa) and release (0 kPa). A copper block (15 × 37 mm^2) whose temperature is maintained at 50°C is positioned at the center of the array marked by the dotted line. The sensing area dimensions are 44 × 44 mm^2. In (d), the pressure-sensor matrix is spread over an egg. Adapted from Ref. 2. Copyright 2005, National Academy of Sciences.

with more native tactile sensitivity. A prosthetic hand wrapped in this sensitive material might be able to handle a delicate object like an egg with exquisite care.

Coupling sensors with radio-frequency communication technology within the E-Skin allows the information it is measuring to be transmitted wirelessly to computers – or conceivably even to other E-Skinned people. At the University of Illinois at Urbana-Champaign, John Rogers' team has taken the first step toward this goal. His latest version of an "electrical epidermis" can be laminated onto your skin in the same fashion as a temporary tattoo.[18,19] The circuits are first printed onto a water-soluble plastic sheet, so the backing can be washed away after the circuit is pressed onto the skin. These tiny devices could be used to monitor a patient's vital signs without the need for wires and bulky contact pads and could also be discretely used by people beyond the confines of the hospital. Rogers' circuits use serpentine squiggles of semiconductors that can be stretched or squished without interfering with their function. He and his colleagues applied circuitry studded with sensors to a person's throat, where it could detect the muscular activity involved in speech. By simply monitoring the signals, researchers were able to differentiate between several words spoken by the test subject. The user was even able to control a voice-activated video game.

A Range of Prospects for E-Skin

Flexible and stretchable electronics are a next-generation technology that will make people's lives safer, more secure, and more comfortable. In addition to the applications described above, sensors could be embedded into objects that come in contact with people, such as clothes, seats, handles, and seatbelts, in order to help monitor their physical health. Large-area pressure sensors placed on the floor of homes could differentiate trespassers from residents by using information such as the size and shape of feet, weight, and the stride length. Large-area pressure sensors



(a) (b) (c) (d)

Fig. 3: (a) Shown is a photograph of printed elastic conductors on a poly(dimethylsiloxane) (PDMS) sheet. (b) Shown is a magnified SEM image of the elastic conductor. Finer or exfoliated bundles of single-walled carbon nanotubes (SWNTs) were uniformly dispersed in the rubber, where they formed well-developed conducting networks. (c) A large-area stretchable active matrix comprises 15 × 15 organic transistors and wiring using SWNT elastic conductors. The printed organic transistors function as active components, while the SWNT elastic conductors function as word lines and bit lines for the interconnections among the transistors. (d) Depicted is a rubber-like stretchable active-matrix organic LED display. Adapted from Refs.13 and 14. Copyright 2008, American Association for the Advancement of Science (AAAS), and 2009, Nature Publishing Group.

embedded in beds could monitor the heartbeat and cardiac motion of patients without causing them stress.

We have not realized all the necessary milestones yet and a great deal of our strategy for improving this device remains proprietary, but we believe that E-Skin will eventually provide humans with not only a new type of man–machine interface but an astonishing range of new applications, many of them yet to be imagined.

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Fewer U.S. Consumers Interested in Buying New TVs

The worldwide television market has been declining since the end of 2011, with global TV shipments down a projected 9% this year on top of a 6% decrease in 2012. With shipments – and profits – shrinking, manufacturers are betting on new technologies such as smart televisions and ultra-high-definition sets to change the grim market outlook.

by Veronica Thayer

THE U.S. TELEVISION MARKET is no exception to the global TV slowdown. In results from a consumer survey conducted by IHS in the U.S. during August 2013,[1] the number of consumers that had not purchased a TV in the past year or were not planning to purchase a set in the next 12 months was rising, from 35% of respondents in 2012 to 53% this year. The main reasons cited by consumers were: "Do not need another TV" and "Purchased one in the last 2–3 years."

Manufacturers are therefore looking to create new incentives for consumers to upgrade their existing sets. Before we examine their plans, it is helpful to take a closer look at the consumer-survey data. The above-mentioned results point to two major current issues in the TV market. First, the number of TVs per household is reaching saturation point in the U.S., as most consumers own at least one flat-panel TV. Second, consumers are increasingly getting used to accessing video content on other devices such as laptops, tablets, and smartphones, raising the question as to whether such devices are affecting the need for a secondary TV set.

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TVs *vs.* Tablet Ownership

One inquiry answered by survey results is whether tablet ownership affects TV purchase intent and screen-size preference. In terms of overall TV purchase intent, survey results revealed that tablet ownership did not cause any variance, with 20% of owners and non-owners alike planning to purchase a TV within the next 12 months.

However, the percentage of consumers purchasing a TV in the past year was nearly twice as high among tablet owners. They showed a clear preference for bigger screen sizes, with 49% of tablet owners preferring a 40–49-in. screen size and 16% preferring 30–39-in. sizes. Non-tablet owners were 32% and 33%, respectively, with regard to these sizes. Demand for 50-in. and larger screen sizes was unaffected by tablet ownership.

The modern connected household frequently contains more than one device with which to access the Internet and from which to consume content. Of the consumers surveyed, 68% owned at least a smartphone, tablet, or smart TV. Nearly 56% of smart-TV owners also owned a tablet and smartphone, and nearly 10% of total respondents owned all three devices. The survey's results imply that not only can smaller screens be complementary to smart TV ownership, but that there is substantial opportunity for companies in the multi-screen video delivery ecosystem to take advantage of the smart-TV installed base.

Smart TVs and Their Impact

While tablets and smartphones have propagated through the U.S. market with lots of momentum, one of the clearest bellwethers of the connected home's evolution is the connectivity of TVs; *i.e.*, the extent to which consumers are connecting the primary media consumption device in the home to the Internet. Although U.S. consumers show relatively high awareness of the term "smart TV," in fact they have a very shallow understanding of what a smart TV does and the kinds of services to which it provides access. In fact, the term "smart TV" is rather loosely defined, but generally means a TV that is connected to the Internet and provides computer-like capabilities such as access to video playback, apps and games, social media, and more.

Among the 2013 survey respondents, smart-TV awareness is at 87%, with the term mostly perceived to denote a TV set that connects to the Internet. Even so, respondents showed less understanding of what that does for them and how it can improve the TV watching experience. A surprisingly high 88% of respondents stated they connected

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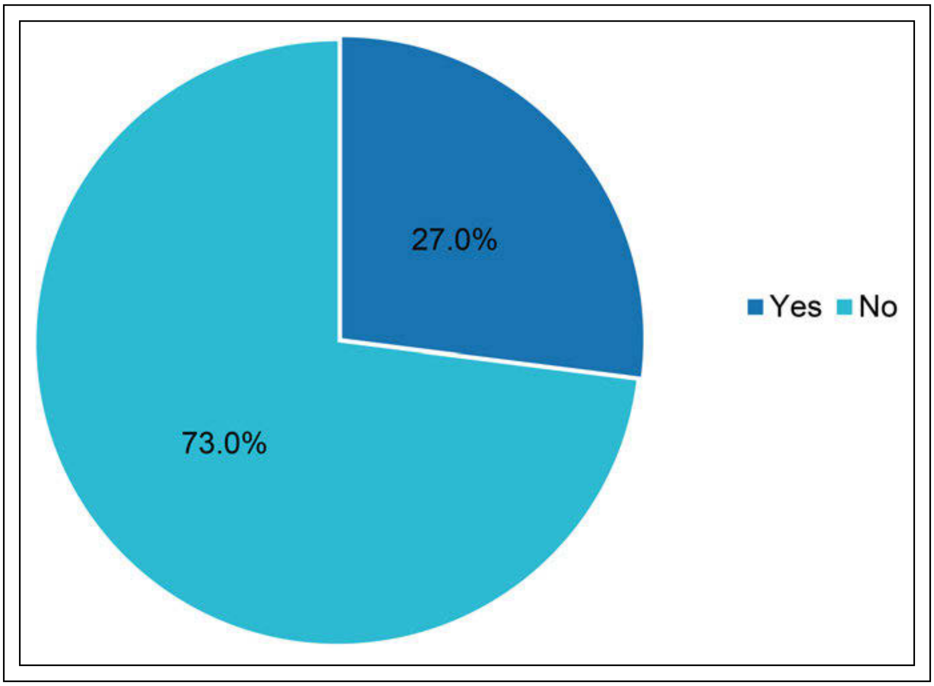

Fig. 1: More than a quarter of customers surveyed who do not currently own a smart TV plan to buy one in the next year. Source: IHS.

their smart TV to the Internet *via* Wi-Fi, Ethernet, or dongles. Pay-TV through the set-top box continues to be the main source of video entertainment in the home. Most consumers are not familiar with the capabilities of smart TVs and all the video content they can access through them.

Still, more than a quarter of consumers expressed their intent to purchase a smart TV within the next year (Fig. 1). Samsung and Sony are the top brands considered for a smart-TV purchase, with about 70% of consumers preferring these two. The top brands considered for purchase are reasonably aligned with their prevailing market share of smart TVs. These five most popular brands are, in order, Samsung, Sony, LG, Vizio, and Panasonic.

Beyond individual brand-purchase intentions, getting consumers to specifically adopt smart TVs continues to arguably pose the same challenges that have existed since the category came into being. In order for smart TVs to be widely adopted, there are indications that consumer-electronics manufacturers will need to invest more deeply into generating greater awareness of such sets and their value proposition.

In general, consumers unaware of smart TVs seemed no more inclined to purchase them beyond the average level seen in buying TV sets, with purchase intent within the next 12 months registering only 7%. Meanwhile, for those aware of smart TVs, the intent increased to 31%. Manufacturers desiring increased adoption of their smart TVs will need to ramp-up efforts, from advertising to point-of-sale branding to retail associate training, to increase mainstream awareness of the product category while boosting understanding of the value and capability offered.

One good sign for smart TVs is that among devices being used to watch Internet video, consumers are relying more and more on such sets as their go-to device. A primary reason is simplicity: smart TVs are less complicated to use than conventional TVs, as they require only one remote and feature a consistent user experience. This compares favorably to more prevalent methods of TV operation that require the switching of video sources, juggling among different devices, and negotiating clunky user interfaces.

Yet, a considerable amount of progress must be made by manufacturers for wider adoption by consumers. Many of those who purchase smart TVs do not use the connected features very heavily, even when they are connected to the home wireless or wired Internet. The results indicate that among smart-TV owners surveyed, more than 11% of those who had their sets connected did not actually use any of the applications on the television.

The Eclipse of 3D television, and the Rise of UHD

One TV feature that consumers are not particularly excited about is 3D (Fig. 2). Results show that only 9% own a 3D TV, and among consumers who do not currently own a 3D set, only about 10% are interested in purchasing one in the next year. Instead, an overwhelming majority indicates no need for a television with this feature. Additionally, 22% of 3D TV owners have never used the 3D function on their sets.

It is also now evident that the market's focus is shifting toward 4K resolution – four times the resolution of standard full-definition 1080*p*. A number of manufacturers have launched UHD products since the third quarter of 2012. The new technology has already brought about price competition, mostly due to the entry of lower-priced, second-tier brands.

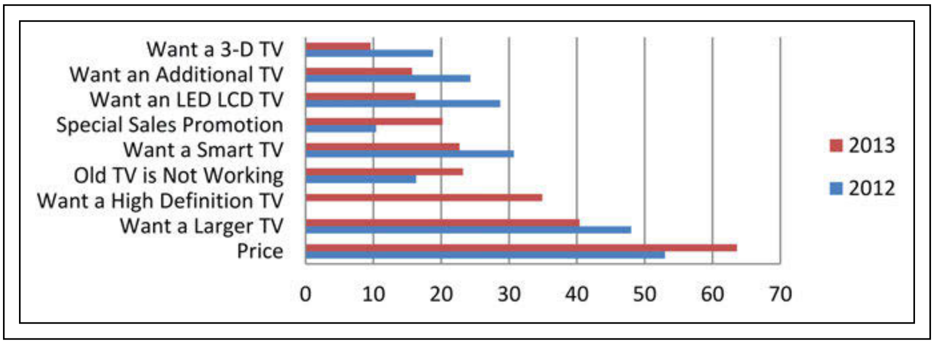

Fig. 2: Price outweighs all other motivational factors when it comes to buying a TV, both in 2013 and 2012. Source: IHS.

But while UHD now promises to be the next big thing in televisions, various factors – the lack of native 4K content, high retail pricing, and the need for big-screen TVs in order for viewers to genuinely appreciate the technology – mean that it will take time for UHD to resonate with consumers and for content developers to back the advanced mechanism.

Survey results confirm this, with only 13% of respondents indicating interest in purchasing a UHD TV in the next year. Among consumers not interested in buying, 40% indicate high price as the main hurdle.

Still, given how far high-definition TV has come since its inception, there is hope for the future success of 4K-resolution TVs and for consumers to eventually warm to their appeal. Recent survey results show that higher resolution is the third-biggest purchase motivator for new televisions behind screen size and price, with 46% of consumers being "very" or "extremely" willing to pay more for higher resolutions.

This seems to indicate that as more UHD TV models enter the market and as prices come down, the sets not only will be sold in greater quantities, but may also be deemed appealing enough for consumers to make that all-important commitment to buy. If consumers become more familiar with the advantages of smart TVs, this capability may spur purchases as well. Looking farther ahead, it seems likely that it will become more difficult for brands to differentiate themselves and that prices will continue to decline. Certainly, larger-screen sizes with added features such as connectivity will become the norm, and TV viewing will become more interactive and more interconnected with mobile devices.

References

[1]The study comprised 1000 respondents in the U.S. ■

Coming Up in the Next Issue of *Information Display* Magazine

Display Week 2014 Preview and OLED Technology

- Display Week Preview
- Honors and Awards Winners
- Displays at CES
- LTPS or IGZO for AMLCDs or AMOLEDs
- Paper Electronics
- Testing Curved OLED TVs: Part 2
- University Research Start-Ups

guest editorial

Momentum for Materials

by Ion Bita

It is my pleasure to welcome you to a new issue of *Information Display* magazine and to wish you a whole-hearted "Happy New Year" as we begin 2014.

One of the topics we are highlighting in this issue is materials and their role in advancing information displays. Reflecting back on the evolution of the technology and on the new product landscapes of the past year, two trends stand out relative to this topic: advancing display image quality and enhancing the capabilities for user interactivity. While it is outside the practical scope of this note to survey in detail the many relevant developments in each of these areas, let me pick just a few that will help provide context for the Frontline Technology articles on materials in this issue.

Among other drivers, the pursuit of TV displays with increased resolution (to 8K ultra-HD) and refresh rates (to 240 Hz for OLED TV) has been fueling intense work on amorphous metal-oxide-based TFTs. The display community is already looking beyond the recently established InGaZnO (*i.e.*, IGZO) family of materials in order to develop alternatives with higher electron mobilities (*e.g.*, InSnZnO and ZnON) and to maintain manufacturing scalability to Gen 8 (2.2 × 2.5 m) glass substrates.[1] In the area of image quality, a material that received renewed accolades last year is semiconductor quantum dots as used in backlights to enable LCDs with color performance rivaling that of OLEDs.[2] Among early stage developments, we should also note the introduction of a new class of "hyperfluorescent" organic molecules that allows light emission from initially triplet excited states and thus achieves high light-emission efficiencies comparable to those of organometallic phosphorescent complexes, the backbone of most of the current OLED display products.[3]

Given the current importance and increasing impact of OLED displays, we are fortunate to include in this issue an article that addresses the present and future of OLED materials. With the perspective of an established materials provider to this industry, authors Kai Gilge, Ansgar Werner, and Sven Murano from Novaled AG (Germany) examine the properties of the organic chemical compounds required for compatibility within the current OLED-display manufacturing infrastructure and highlight material requirements expected to be critical in next-generation platforms.

As mentioned in the introduction, another important trend that is shaping the evolution of information-display products is enhancing capabilities for user interactivity. Touch screens are now the main input interface for smartphones and tablets and are on a path for widespread adoption in most portable computing devices. With projected-capacitive touch sensing as the dominant technology, transparent conductor materials have become a subject of renewed interest. As reviewed in an earlier issue of *Information Display* by Paul Semenza,[4] indium tin oxide (ITO) is a standard choice due to the extensive experience that manufacturers have accumulated over decades in the use of display panels. New requirements for improved electrical, mechanical, and optical properties, adding to the drive for reducing the cost of touch sensors, have led to the development of ITO alternatives based on conductive nano- and micro-structured materials (metal meshes, silver nanowires, metal nanoparticles, carbon nanotubes) as well as conductive films (polymers, graphene sheets). Furthermore, the need for an efficient fabrication of sensing electrode structures in the display stack has led to additional material and processing innovations that are now enabling a transition

(continued on page 50)

Applying OLEDs in a Manufacturing Process

The organic chemical compounds used in OLED display manufacturing require careful appreciation, characterization, and analysis. When they are paired with the right manufacturing processes, impressive results can be achieved.

by Kai Gilge, Ansgar Werner, and Sven Murano

SINCE the first publication of modern organic light-emitting-diode (OLED) structures by Ching Tang and Steven Van Slyke in 1987, a billion-dollar business has evolved, mainly due to the huge success of active-matrix OLED (AMOLED) displays in recent years. Along with this industrial success came significant developments and improvements in device manufacturing, especially with regard to throughput and substrate size. The dominant material deposition technology, however, remains the same as in the first fundamental work by those early Kodak researchers – thermal evaporation under high-vacuum conditions. Of course, in order to enable industrial application of this evaporation coating technique, several challenges had to be overcome with regard to tools, processes, and materials.

In this article, we will examine the material properties of the organic chemical compounds used in today's OLED display processing landscape and highlight additional requirements expected to become critical for the next generation of displays. We will also provide insight into how these properties can be tailored during the product development process. Finally, we will offer a glimpse at what OLED manufacturing might look like 5–10 years from now.

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Deposition Equipment Developments

To better understand the material requirements for organic semiconductors in OLED manufacturing, it is necessary to examine the processing details. The original thermal evaporation deposition process used small crucibles as "point sources" to deposit thin films onto static or rotating substrates under high-vacuum conditions (typically in the order of 10^{-7} mbar). Such sources can be described as open evaporation, *i.e.*, the molecules in the gas phase can directly enter into the volume of the vacuum chamber. This process is not very efficient and cannot be scaled to larger substrate sizes due to a combination of reduced uniformity and a relatively low material deposition yield (typically in the range of just 5%). Therefore, improved deposition tools were developed based on linear sources in which the material is deposited across the entire width of substrates that are moved linearly along the source opening (Fig. 1). In this way, the material usage can be increased significantly and upscaling to large motherglass sizes becomes feasible. The typical substrate size used in AMOLED production is Gen 5.5 (1300 × 1500 mm); however, there are plans by Samsung Display and LG Display to ramp up Gen 8 lines for TV production in the near future. With state-of-the-art source systems, a material utilization of 15% can be achieved.

While addressing utilization and scalability challenges, modern linear sources introduce additional challenges related to the increased thermal stress imposed on the organic material. Linear sources are usually semi-open systems, which means that inside the source the pressure is greater than in the surrounding tool

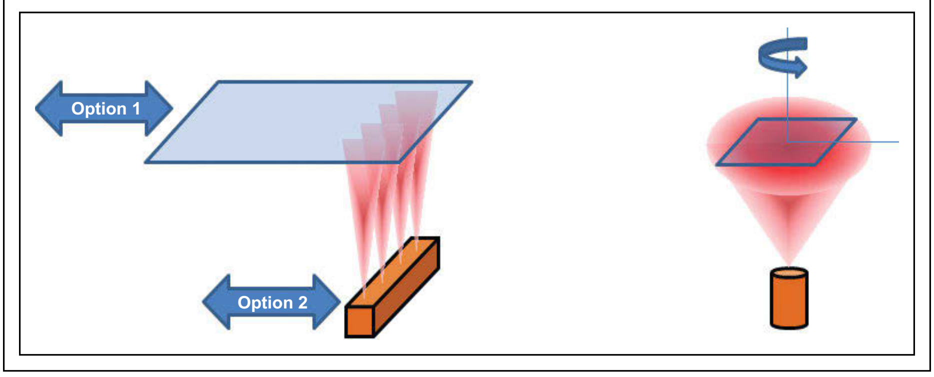

__Fig. 1:__ At left, a simplified linear-source deposition process is depicted and at right, a point-source evaporation process. For the linear-source deposition concept, either the substrate (option 1) or the source (option 2) can be moved.

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chamber, and the evaporated particles are distributed evenly throughout the inner volume of the source by intermolecular collisions.

Furthermore, because linear-source architectures require increased partial pressures inside the source for distributing the material homogeneously, the nozzles of these sources have to be set to a temperature well above the evaporation point in order to prevent clogging. Thus, the material reservoir is exposed to a permanent thermal stress for a duration of several days or even weeks. Figure 2 shows typical linear nozzle source equipment.

An important metric for the processing quality of linear-source systems is the homogeneity of the deposited layer across the substrate, which typically needs to be in the range of ± – 5%. Another important requirement is to maintain stable deposition behavior throughout the entire processing cycle, *i.e.*, the layers have to be of the same morphology on the first and the last day of operation.

Thermal Material Requirements

Due to the adoption of linear-source architectures, the materials used in OLED manufacturing require a chemical development focus toward achieving a larger thermal stability gap. This is defined as the difference between the evaporation temperature and the thermal decomposition temperature of the considered material. In order to determine this gap, developers usually check the evaporation temperature at the onset of processes in an open evaporation source

In order to determine the thermal-stability window of materials, different measurement approaches can be used. A fast screening method is thermal gravimetric analysis (TGA), in which the material is heated in a controlled way while the sample weight is monitored. Most frequently, this measurement is conducted in an inert-gas stream. TGA can also be carried out in high-vacuum conditions, but such instruments are less available and rather costly.

The point where the material loses 0.5 % of the original mass is defined as the decomposition temperature. This procedure has to be exercised with care since weight loss could be caused by volatile impurities, such as solvents, without the actual decomposition of the main compound. Since virtually all OLED materials for vapor deposition are purified by gradient sublimation, it is typically expected that volatile constituents have already been removed during the purification process.

Fig. 2: This linear-nozzle-source deposition equipment is from Sunic Systems in Korea.

The presence of volatiles in the final quality of the compound indicates issues with the purification or with the stability of the material in the sublimation process.

Another source for weight loss during TGA could be, of course, sublimation itself. However, due to the low vapor pressure of most OLED materials, decomposition of the compound is typically observed before sublimation at ambient pressure. By combining TGA with DSC (differential scanning calorimetry), it is relatively straightforward to identify the physical origin of the observed mass loss and to properly identify the decomposition temperature.

If the decomposition temperature and the evaporation temperature are close, this is a strong indication for a limited thermal stability of the compound. TGA experiments are usually conducted within 1 hour or less. TGA is, therefore, particularly useful as a screening method in the early development stage of materials. However, TGA just measures fast degradation processes and does not give much information about thermal stability over an extended time period. Hence, organic compounds that can successfully pass TGA tests still require further stability investigation.

It is tempting to use TGA in a more sophisticated way to assess long-term thermal stability. One approach would be to record the TGA data for various heating rates and fit the resulting spectra to kinetics models of the decomposition process. Except for the simplest cases, the authors found the precision of this procedure insufficient to predict the stability of the material in a real condition. The main obstacles are extrapolating over more than one order of magnitude in time, and the difficulty in identifying appropriate kinetic models matched to complex decomposition processes. Consequently, a better approach is needed.

We are currently conducting long-term thermal-stability measurements in quartz ampoule tests. The materials are placed in closed evacuated quartz ampoules at a range of temperatures (*e.g.*, T_{evap}, T_{evap} + 25 K, T_{evap} + 50 K, T_{evap} + 75 K) for a specific period of time. After the test is complete, the materials are visually inspected and chemically analyzed in order to determine the effect of the thermal stress on the materials. In addition, actual OLED devices are built with these new materials and fully tested, which provides direct verification of the material stability at a given temperature. By using this test method, it is possible to determine the thermal-stability window for a specific material.

Due to their semi-open nature, linear sources require organic materials with a thermal stability at temperatures 20 K and more above T_{evap} that are maintained for several days. Only in this case can it be ensured that the OLED device performance is stable even for devices fabricated after several days of consecutive processing from a given material batch.

An Electron-Transporting Material

In order to better describe these trends, the authors examine a particular example in more detail, comparing the Novaled electron-transporting material (ETL) NET-164 to a state-of-the-art ETL used in display manufacturing. Table 1 shows calorimetric data of the two materials together with the evaporation temperature measured in an open-source vacuum-deposition tool.

When comparing these two materials with TGA, the authors found that both show a sufficiently large gap between the evaporation temperature, and also a 0.5% weight loss decomposition (ΔT for NET-164 = 168 K, ΔT for SoA ETL = 132 K).

In this stability test, it can be observed that the SoA material already fails at a temperature of T_{evap} + 75 K, whereas NET-164 still shows good performance at T_{evap} + 100 K.

Table 2 shows the data generated from the two materials sealed in quartz ampoules. This table shows ampoule temperatures at which the materials were tested. The green (pass) or red (non-pass) color indicates whether the material was still indicating good quality after the test. These tests were conducted for 10 days at the temperatures indicated in the table.

Figure 3 shows the pictures of two ampoules with the SoA ETL measured at 318°C (left) and 368°C (right). One can clearly see the brownish coloring of the sample exposed to the higher thermal stress. This goes along with a strongly reduced analytical quality (*e.g.*, HPLC purity) and deteriorated OLED device performance.

For material developers, it therefore becomes increasingly important to improve the thermal stability of the materials. This can be in conflict with other optimization parameters, such as lifetime or efficiency, but, in particular, with the glass-transition temperature of the organic compounds. Almost all OLED materials form organic glasses with amorphous layers, which prevent crystallization and give rise to favorable morphologies of the organic semiconductor layers. The temperature at which these organic glasses soften determines the glass-transition temperature. This softening can lead to a breakdown of the OLED devices, *e.g.*, via mixing of adjacent layers or due to other inter-diffusion phenomena in the device stack. For that reason, device manufacturers request materials with rather high glass-transition temperatures, which typically translates to higher evaporation temperatures. These higher evaporation temperatures finally tend to narrow down the

Table 1: *Calorimetric data for two materials (NET-164 and SoA ETL) measured in an open-source vacuum-deposition tool include T_g (glass-transition temperature), T_{evap} (evaporation temperature), T_m (melting temperature), TGA 0.5% (temperature of 0.5% weight loss in TGA), and TGA 5% (temperature of 5% weight loss).*

Material	Tg (DSC)	T_{evap}	Tm,peak (DSC)	TGA 0.5%	TGA 5%
NET-164	110°C	227°C	251°C	395°C	447°C
SoA ETL	171°C	293°C	354°C	425°C	496°C

Table 2: *Data generated from the same two materials sealed in quartz ampoules show SoA ETL failing at a temperature of Tevap +75 K.*

Material	Test Duration (d)	T_{evap}	+25 K	+ 50 K	+75 K	+ 100 K
NET-164	10	227°C	252°C	277°C	302°C	327°C
SoA ETL	10	293°C	318°C	343°C (no data)	368°C	393°C

Fig. 3: *The ampoule on the left shows the SoA ETL material measured after exposure at 318°C and the one at right, the same material after exposure at 368°C.*

thermal-stability window of compounds, which means, in other words, that the requirements for high thermal stability as well as for high glass-transition temperatures in many cases oppose each other.

This basic trend can also be observed when the two ETL examples, NET-164 and the SoA material, are compared. Here, NET-164 has a glass-transition temperature that is 61 K below that of the SoA material. A similar difference is observed in the evaporation temperature, which is 66 K lower for NET-164. However, it is found that NET-164 is not only more stable than the reference material relative to the evaporation temperature, but also exhibits long-term stability when compared with the SoA material at the same temperature. This indicates that a selection of robust chemical structures can help reduce the tradeoff between T_g and stability requirements.

Inorganic materials are sometimes proposed for use in OLED devices. Indeed, such materials exhibit very high thermal stability and usually do not decompose during physical vapor deposition. However, they raise other issues such as limited environmental stability, safety concerns, difficult thermal management due to very high evaporation temperature, and difficulty in measuring evaporation rate or formation of dust. Some salt-type materials exhibit decomposition by forming neutral products before volatilization, which is usually accompanied by the formation of gasses and volatiles that are difficult to control.

Other Material Requirements

In addition to the thermal properties and stability of the organic materials, many other parameters need to be optimized, such as the energy levels of the highest occupied molecular orbital (HOMO) and the lowest unoccupied molecular orbital (LUMO), the charge carrier mobility for holes or electrons, the quantum efficiency for emitting materials, *etc*.

In many cases, the optimization of these parameters depends strongly on the environment in which a material is used. For example, the requirements for an ETL material in a blue monochrome device (such as an RGB display structure) might be completely different than the requirements in a tandem white OLED. A tandem structure is a more complex device structure in which two mono-chrome OLED units (*e.g.*, yellow and blue) are stacked vertically to provide, in combination, white light. This structure has merits in light output and durability because it creates double the amount of photons per unit area. Furthermore, the creation of the primary colors from white OLED using color filters has advantages over using red, green, and blue OLED pixels if high pixel pitch and patterning on a large area are required.

It is well-known[1] that blue OLEDs exhibit a tradeoff between lifetime on the one hand and operating voltage on the other. In order to maintain a certain operational stability in the device, as required by the target application, a compromise in operating voltage has to be accepted. The yellow unit of a tandem white structure does not exhibit the same interplay. Consequently, an ETL with a lower operating voltage can be employed. Another illustration of this principle is the case of solution-processed OLEDs using vapor-deposited ETL to optimize performance (hybrid structure). Here, the proper adjustment of LUMO level to the polymer EML and the morphological state of the interface between polymer EML and small-molecule ETL layers is essential.[2]

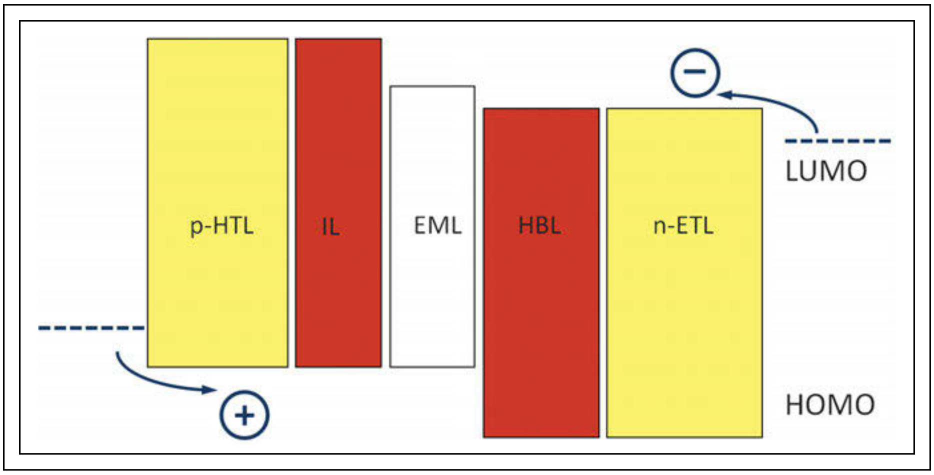

***Fig. 4:** An energy-level diagram of a typical OLED device depicts the highest occupied molecular orbitals (HOMO) and lowest unoccupied molecular orbitals (LUMO) of the organic materials used in the layer sequence.*

Figure 4 provides an energy-level diagram of a typical OLED device. It depicts the highest occupied molecular orbitals (HOMO) and lowest unoccupied molecular orbitals (LUMO) of the organic materials used in the layer sequence. The two orbitals can be likened to the valence band and conduction band, respectively, of inorganic semiconductors. In contrast to inorganic semiconductors, the electronic states of holes and electrons are localized on individual molecules and charge transport takes place by hopping between individual sites. In the figure, the light-emitting layer (EML) is in contact with the hole-transporting layers (left side) and electron-transport layers (right side), facilitating charge injection and transport from the electrodes to the EML. In comparison to EML materials for vapor deposition, polymer emitting materials frequently have a very high lying LUMO level; *i.e.*, injection of electrons into the EML is more difficult. In consequence, LUMO levels of hole-transport layer (HBL) and electron-transport layer (ETL) have to be adjusted to reduce injection barriers. n-type doping of the ETL is required for efficient charge injection into the organic layers. In consequence, the development of functional parameters of new materials should be done for each specific application – there are too many variables to make one universal material.

Future Developments

The current manufacturing trends for large-area glass substrates may already be pushing some materials to their thermal limits. However, the increasing price pressure of the markets demand that tact times for the tools go down further, which reduces processing times for the individual layers and therefore requires even higher deposition rates. There is certainly room for further optimization of the thermal durability of individual materials, but at a certain point, the limits of organic chemistry will prevent even higher processing temperatures. For these reasons, tool manufacturers are investigating new deposition source concepts that apply less thermal stress on the materials.

In addition, manufacturers are interested in increasing tool up-times by enhancing the production time between necessary tool maintenance. This enhances the material amounts that are needed during the production cycle, and also increases the duration of the thermal stress on the materials.

One additional challenge in this respect is the need to distribute the heat equally in the sources to avoid any hot-spot formation, which could cause localized material degradation (*e.g.*, at nozzles, tubes, *etc*.). For this reason, and due to the limited filling volume of the current concepts, most tool manufacturers are developing feeder mechanisms to allow an upgrading of the material loads. This can be realized, for example, by means of revolving material compartments, which can be evaporated one after another.

Another attractive concept is the use of feeder sources, in which the material powder is loaded into the evaporation zone of the sources via spiral conveyors. However, thus far these implementations suffer from clogging or jamming of the material powders. A potential future requirement for materials might be compatibility with such feeder-source approaches; however, this approach has not been realized and the specific material properties that might be required are not fully clear at the moment. One way to approach this topic might be pelletization of the materials, which is mostly only possible through the mixing of the active compounds with caking agents. If and how this can be realized in the future remains to be seen. Other potential future material evaporation concepts might use carrier gases (*e.g.*, already followed by the so-called OVPD process – organic vapor-phase deposition). Here, also, detailed material requirements cannot be deduced at the moment, but such approaches often require heating of tubes and shower heads to temperatures well above the evaporation temperature of the compounds, thus increasing the thermal stress on the materials.

One further interesting development is the emerging technology of printable OLEDs based on solution processing, such as ink-jet printing, spin-coating, or slot-die coating. There are very fundamental differences in the deposition processes as well as in the material requirements between evaporation and solution processing. Whereas one process is based on rather small molecules that can exist in the gas phase, the other is usually based on polymeric or oligomeric compounds that are optimized for solutions in organic solvents.

The potential move away from evaporation toward solution-processing sets very different challenges for material developers. These, however, go beyond the scope of this article.

In the meantime, a thorough understanding of the material properties of the organic chemical compounds used for OLED deposition will help developers and manufacturers refine their processes for today and tomorrow's display requirements. A great deal of research has gone into fine-tuning these processes for industrial applications, and that research is ongoing.

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New Electro-Mechanical Polymer Actuator Technology for Better Interactivity

Smart material actuators for haptics may help usher in a "New-Sensory Age."

by Christophe Ramstein and Ausra Liaukeviciute

MOBILE DEVICES such as smartphones, notebooks, and wearables are rapidly transitioning into what we are dubbing the "Neo-Sensory Age" – the next phase in the evolution of computers in which devices become more personal and portable and, most importantly, in which the interface between user and computer spans all the human senses. By fully engaging the senses, the computing devices of this new age will enable immersive, effective, and multimodal interactions. In this article, we will review new materials and enabling technologies for haptics, one of the core elements of a sensory user experience that complements touch-input interfaces with tactile output.

Although essential in real life, haptics is missing or poorly implemented in today's mobile-computing devices. Since the first mobile phones introduced vibrational alerts as a complement to audio ringtones (the Motorola StarTAC in 1996, for example), most mobile phones have included some sort of haptic-feedback solution to provide users with tactile notifications. Most typically, mobile phones employ so-called whole-body haptics, in which the entire phone vibrates when it receives a call. More recently, the use of whole-body vibrations has expanded to confirm key presses while typing text, and also for making gaming and entertainment applications more engaging. This is an inexpensive yet bulky and limited performance solution that uses small motors to deliver vibration to the mobile devices. Eccentric rotating masses (ERMs) and linear resonant actuators (LRAs) are the most popular conventional technologies for these simple buzzes; these have not changed very much over the last 15 years.

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Such conventional actuators offer limited product-design flexibility. They are not able to support the new generation of component requirements for slim and powerful mobile devices. In addition, product designers are searching for ways to deliver a richer and more realistic and advanced haptic-user experience as a key product differentiator.

Electro-mechanical polymers (EMPs), a new type of electro-active polymers (EAPs), have emerged as a leading candidate to address the growing demand for a new actuator technology – one that is thinner, lighter, and bendable, with a large tactile and audio-response range enabling a richer user experience while providing more design flexibility to the mobile-device vendors. This article reviews this new haptic technology and highlights the important role EMP actuators will have in the emerging "Neo-Sensory Age." It will discuss the need for these actuators, examine the properties and capabilities of EMP actuators, compare and contrast them against other technologies such as piezoceramic (PZT) actuators and dielectric elastomer EAP actuators (dEAPs), and describe the applications for these actuators.

Haptics for Flexible Displays and Consumer Devices

When we think of our most important senses, vision, hearing, and touch come to mind – but what we often overlook is the fundamental importance of haptics, or touch feedback during interactions with our surrounding environment. The thousands of sensors located in our skin[1] are the main tools we use, not only to orient ourselves spatially and physically, but also to perceive and learn about the world around us. It is through these receptors in our body and in our skin that we gain vital information that guides our interactions with the nearby environment and enables us to differentiate textures, sense pressure, feel vibrations, and experience temperature.

The human hand is richly endowed with these tactile receptors.[1] Each hand has approximately 150,000 mechanoreceptors. Their density is highest on the fingertips (2500/cm^2). These receptors provide tactual acuity, enabling humans to discriminate fine surface texture, instantaneously identify object contours and shapes, recognize material types, and control hand motion.

Most existing touch-screen devices, such as smartphones and tablets, support an increasing array of multi-finger gestures. Users can scroll, pinch, swipe, zoom, and rotate with multiple fingers. This makes the user interaction rich, natural, and intuitive.

From a tactile feedback standpoint, we should expect these multi-touch devices to provide a similarly rich tactile response, one that localizes the tactile response to each

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finger. Unfortunately, whole-body vibration solutions integrated into current multi-touch touch-screen devices are limited to one vibration at any given time for the entire device. This makes the user's experience incomplete. To leverage the full potential of our bodies, hands, and fingers, future flexible displays should have localized haptics to enable a true multi-touch multi-haptic experience.

To create localized haptics on multi-touch devices (Fig. 1), designers and engineers will have to re-think mobile devices and integrate multiple actuators that can create haptic responses in multiple areas of the device in the form of localized vibrations, sounds, and deformations. These will be simultaneously and fully synchronized with the multi-finger gestures being performed. Each finger should receive its own tactile response. Such actuator technology cannot be realized with existing bulky motors. These haptic devices will need to be ultra-thin, ultra-light, and easy to integrate with the cover or the touch screen of flexible devices.

Review of Smart Material Actuator Technologies for Haptics

New actuator materials are required to enable the devices described above with multi-touch input and localized haptic, sound, and touch capabilities. The actuator material will need to allow high electro-actuation strains, meaning that it will be pliant enough to deform or stretch, yet strong enough to handle high stresses and move structures that transmit vibrations. This elastic energy density, the product of strain and stress, is one of the key metrics for quantifying the overall performance of actuator materials.

A new generation of haptic devices under development focuses on solid-state actuator technologies based on thin, smart materials with significant mechanical response to electrical stimulation (Fig. 2). Relevant material choices include piezoceramic material, such as lead zirconate titanate (PZT); dielectric electro-active polymers (dEAPs), such as soft elastomers that allow compression by electrodes under electrostatic Coulomb attraction; and electro-mechanical polymers (EMPs), such as relaxor ferroelectric electrostictive polymers [*e.g.*, poly(vinylidene fluoride – trifluoroethylene – 1,1-chlorofluoroethylene), or P(VDF-TrFE-CFE), and poly(vinylidene fluoride – trifluoroethylene – chlorotrifluoroethylene), or P(VDF-TrFE- CTFE)].

Piezoceramic Material

Piezoelectric ceramic technology, widely used in the consumer-electronic space, is used for speakers, sensors, and vibrational motors. PZT materials, which actuate by bending and changing shape through an electrical polarization process, are capable of producing a considerable amount of force (see Table 1). These ceramic-based materials, though strong, are brittle and susceptible to breakage, which is a challenge for flexible device configurations. Moreover, they can only produce small strain levels. In bending actuations, the maximum strain of typical piezoceramics is only 0.05%. Thus, for a 100-mm-long device, the length change in electro-actuation would only reach 0.05 mm (Fig. 3).

In fact, the elastic energy density of these materials is less than 0.01 J/cm^3. Owing to their rigid nature and low strain capabilities, piezoceramics have a limited potential for use in developing devices with advanced localized haptic feedback and compatibility with flexible architectures.

Dielectric Polymers

Among the polymer-based actuators, dielectric EAPs use electrostatic forces created by two electrodes to compress a soft, elastomeric polymer film. Dielectric EAPs are capable of

__Fig. 1:__ Whole-body haptics is insufficient to fulfill the potential of multi-finger actions. Future displays will incorporate localized haptics.

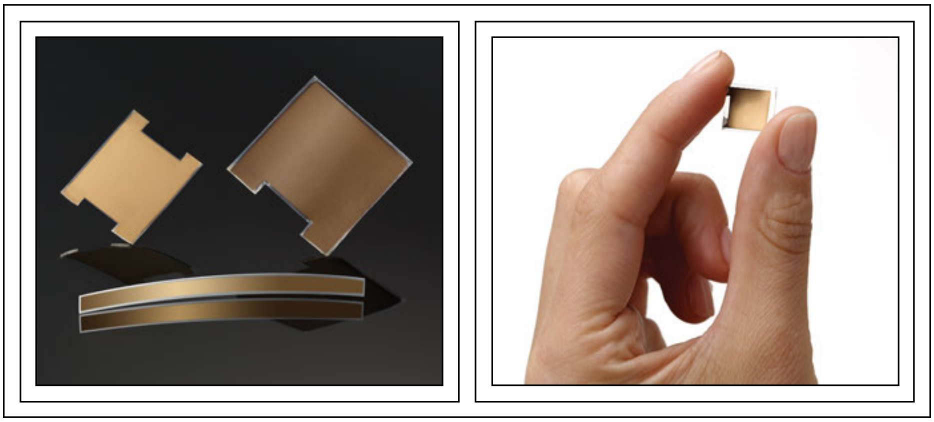

__Fig. 2:__ Electro-mechanical polymers (EMPs) are a new type of device capable of providing haptic responses in a small form factor.

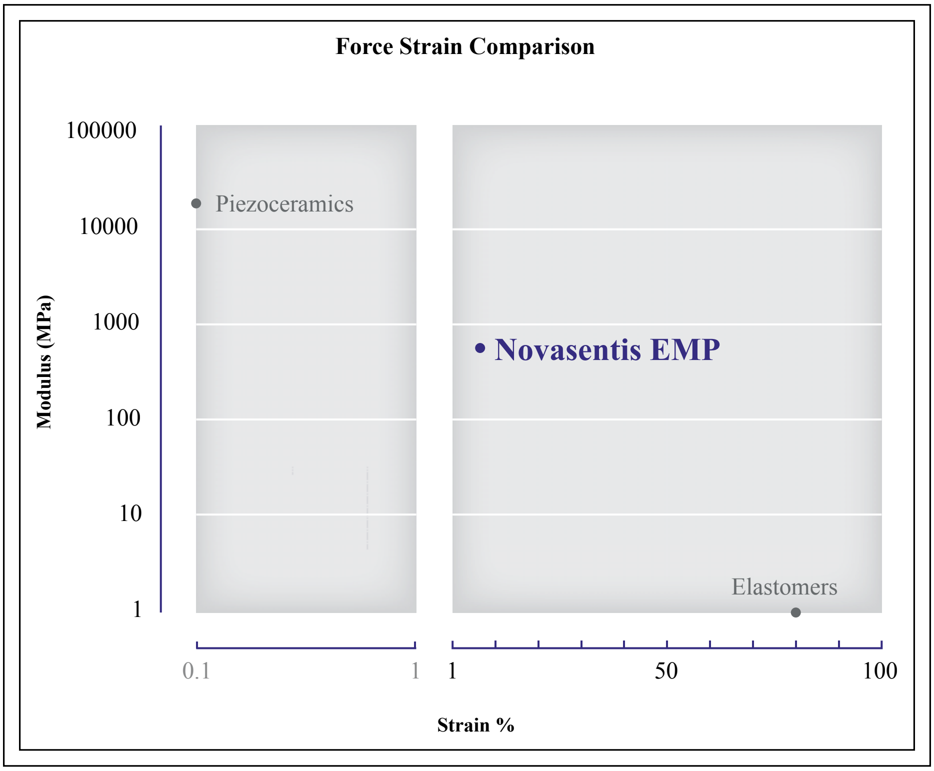

Fig. 3: The strain and modulus of PZT, dEAP, and EMP materials are compared.

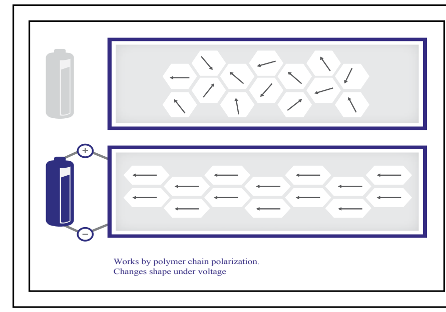

Fig. 4: This electro-mechanical polymer working mechanism shows the elongation of the materials in the lower box.

undergoing high strains, but they provide small forces and typically require high voltages (*e.g.*, over 900 V, low current). When an electric charge is applied, the electrostatic forces acting upon the electrodes can result in either attractive or repulsive forces. The high voltage required is due to the thickness and modulus of the soft elastomeric interlayer. Vibration is achieved by varying the voltage signal. While the movement and potential frequency created with this movement can be high, the stress level is very low, which requires a large device area for generating a reasonable local force for vibrations or deformations. For dEAP, the elastic energy density is less than 0.03 J/cm^3, higher than PZT.[6]

In conclusion, PZT and dEAP material are both good candidates for creating inertial resonant actuators that can shake a mass to create whole-body vibrations. PZT benders are suitable for high-definition resonant actuators (HD LRAs) with a large frequency response (100–300 Hz). They can shake a mass quickly on a short displacement. However, owing to their very low strain, their brittle nature, and their lack of design flexibility, they will not be able to accommodate the need for localized haptics. Similarly, dEAP material will be useful for creating resonant actuators (LRAs) with low-frequency responses and quiet vibrations if the mobile devices can support the high-voltage requirement. However, dEAP material cannot support localized haptic implementations such as localized vibrations and deformations; its low modulus requires very large device areas to produce the required force.

Electro-Mechanical Polymers (EMPs)

EMPs, in contrast, are a new class of EAP materials that offer both large strain and comparatively high modulus. EMP is ideally positioned for creating localized haptics – including vibrations, deformation, and sounds. EMP can also be used as a local pressure sensor. It differs from dEAP and PZT in that the origin of macroscopic deformation is a fast reversible solid-state phase transition in a piezoelectric phase induced by an applied electric field. The external electric field makes the polymer chains transform from one conformation to another structure with different dimensions, causing the material to elongate (Fig. 4).

In contrast to ceramic materials, EMP actuators can achieve much higher strain – more than 3%, which is 60 times higher than that of the ceramic-based material (Fig. 3).[3–5] Furthermore, EMP actuators also exhibit higher elastic energy density, more than 0.2 J/cm^3.[3–5] Therefore, they can generate a great deal more force than dEAPs using a given space. The EMP material is ultra-thin, and EMP actuators are less than 200 µm in thickness. Given this combination of properties, EMPs are an ideal platform for localized haptic applications, sound, and pressure sensing. This class of materials holds significant possibilities for defining a new way of providing localized haptic feedback in consumer-electronics, medical, and automotive products, and other applications across various industries.

Summary of PZT, dEAP, and EMP Material Technologies

Table 1 summarizes key properties of the three smart material actuators described in the previous sections: PZT, dEAP, and EMP. These metrics are key to understanding the benefits and downsides of each technology in the context of flexible displays and mobile applications. As we can see, while PZT is strong enough, the movement it generates is quite low. This combination requires PZT material to be used in a thick (2.5 mm) LRA structure (where mass is added to be shaken), preventing the possibility of attachment to the surface of ultra-thin mobile devices for concentrated localized vibrations. dEAP actuators, on the other hand, have quite a lot of strain (25%), but very low force (1 MPa). This material also requires additional mass in order to vibrate structures in mobile devices. In addition, high voltages required for this technology are not applicable for consumer-electronics devices. On the other hand, EMP material balances strain (3%) and force (700 MPa) and is ultra-thin and flexible, which allows it to be attached directly to the device surface and provide localized vibrations for next-generation thin and flexible devices.

When comparing the inherent properties of the three material platforms discussed, EMPs stand out as the most promising solution for developing thin and light devices and enabling integration of advanced haptics into next-generation displays and consumer electronics.

Table 1: Key metrics for EMP, dEAP, and PZT include strain, modulus, and electric field

Material	Actuator Thickness	Strain (%)	Elastic Modulus (MPa)	Elastic Energy Density (J/cm^3)	Typical Driving Voltage for Vibrations (V)	Electric Field (MV/m)
EMP	<200 µm	3%	700	0.225	[0–150]	80
dEAP	0.5–1.5 mm	25%	1	0.031	[0–1000]	50
PZT	>2.5mm	0.05%	60,000	0.01	[-150–150]	1

Choices for Product Design

When evaluating haptic technologies for displays and consumer electronics, several aspects of the material should be considered: overall form factor, haptic performance, mechanical and environmental durability, power consumption, and operating voltage.

EMPs are ultra-thin, flexible, lightweight, and highly customizable. EMP actuators can directly bond to different surfaces to enable architectures that create localized vibrations, emit sound, and visibly deform. As we can see from Fig. 5, the EMP actuator attaches directly to the surface to create localized vibrations.

The physical properties of EMP actuators offer a variety of options for customization; they enable light and thin mobile product form factors integrated with realistic tactile feedback. EMP actuators can also complement new component technologies, such as flexible displays, to provide a more practical feature set, with haptics and sounds in one package.

Another factor to examine when choosing a haptic actuator technology is performance – the strength and frequency of vibration – and how the vibration feels and performs in different scenarios. All of the smart-material actuator technologies described in this article are capable of operating at a wide range of frequencies (100–300 Hz), generating over 1 g of acceleration – so-called High-Definition Haptics. EMPs provide multi-touch localized haptic vibrations and deformations that are only felt under the specific area touched by the user. This enables a much more realistic tactile interaction with devices and a wider range of actions.

When implementing haptics in mobile devices, it is also important to consider the overall system architecture (Fig. 6). This typically consists of a microcontroller, driver, and power electronics, plus one or multiple actuators and sensors.

For smart material actuators, a key factor is the operating voltage and, therefore, the electrical power-supply requirements. In consumer electronics, dielectric EMPs are not attractive because they require a very high voltage (see Table 1), which greatly limits the selection of and increases the cost of the electrical driver. Piezoceramic and EMP actuators, on the other hand, require much lower voltages. Miniature commercially available drivers for consumer electronics are ideal for driving these technologies.

Haptic Applications for EMP Actuators

Because conventional mechanical buttons

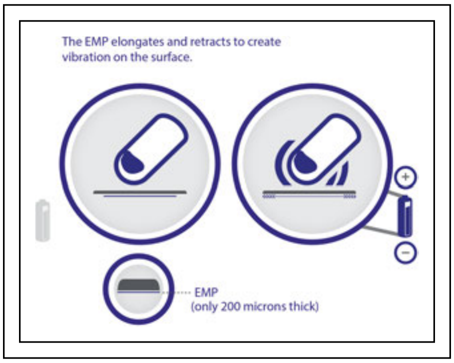

Fig. 5: In the image above, the electro-mechanical polymer is attached to the touch surface.

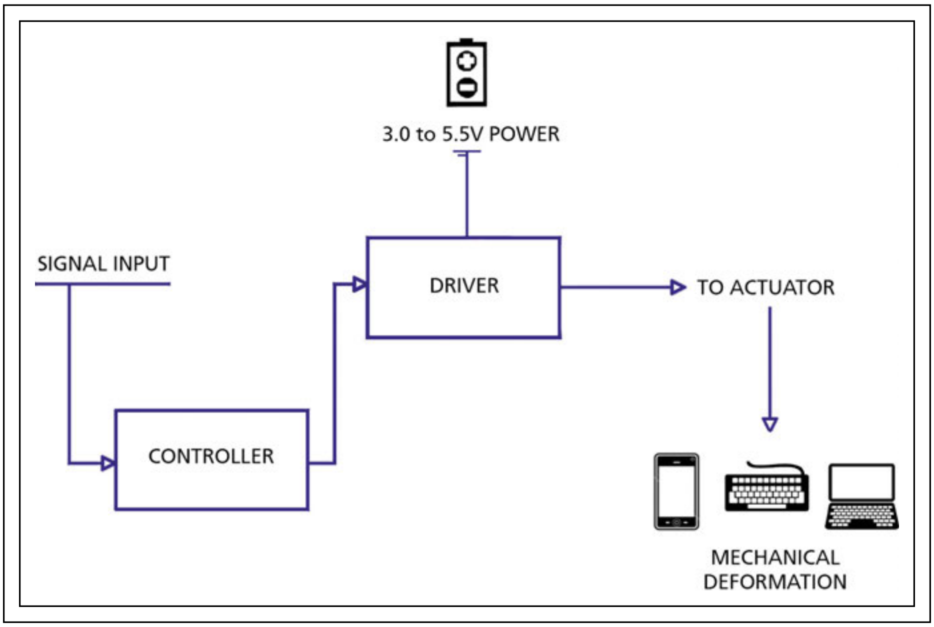

Fig. 6: A typical haptic system architecture consists of a microcontroller, driver and power electronics, and one or multiple actuators and sensors.

seem to be on track for obsolescence, deformable, mechanically programmable user interfaces with dynamic haptic feedback could eclipse the static displays of today. Enabled by shape-changing materials such EMPs, touch screens someday may have physical 3-D buttons emerging from the surface of a portable device on demand.

Some intermediate solutions are being explored to morph buttons out of a transparent surface. For example, a solution developed by Tactus is made from a multi-layered stack with an optically clear polymer on top that deforms when liquid is being pumped in and out through micro-channels. This solution does not offer the ability to control buttons individually, nor to provide local vibrations, and requires liquid management in a mobile device. New technologies will help expand the physical limits of our devices by enriching the user experience in human-machine interfaces.

To get a better sense of how new EMP technology can be utilized in real products, three application examples are provided below: an ultra-thin keyboard, touch screens, and wearable devices.

Ultra-Thin Keyboards with Localized Haptics

While mobile devices get thinner and lighter, a major obstacle to making keyboards thinner is the physical packaging of the mechanisms under each key that provide the desired feel of a snappy "click." Many OEMs are increasingly looking for methods to manufacture thinner and lighter keyboards without sacrificing that physical tactile feedback.

Figure 7 shows an ultra-thin keyboard prototype with localized vibrations and sounds enabled by EMP actuators. While typing on this keyboard prototype, users feel vibrations and sounds on each key to confirm button presses, making the typing experience similar to typing on a keyboard with physical buttons. This prototype, however, only provides vibrations and does not have integrated deformation. The next generation of this prototype will show the ability to bring the keys up when needed, adding the kinesthetic feel of the key shape as well as the snappy feel of a click, without requiring any mechanical structure underneath the keyboard substrate.

Localized Haptics for Touch-Screens

The obvious next step for touch screens is to mimic the shapes of keyboard keys and other UI buttons and icons, directly on the touch screen, while also providing a physical behavior in response to multi-finger gesture. Imagine the keys of a keyboard morphing out of a touch screen so you can feel their shapes while browsing the touch screen with your fingers. While typing, you would get the snappy feel of the click, along with a subtle but localized sound! And once typing is done, the touch screen would go back to its original flat and smooth shape, better for swiping and scrolling gestures. To create a morphing touch screen, transparent EMP will be required, along a thin, compliant, transparent substrate to replace the glass. Transparent EMP actuators are currently under development.

Haptics for Wearable Devices

Wearable devices such as watches, goggles, shoes, and many others under development are an extension of smartphones, tablets, and notebooks. They are smaller, thinner, and lighter, with limited power. They have less and more specific functionality and very small and limited displays for interaction. Therefore, an alternate mode of feedback is required to give end users simple information such as alerts and notifications. Later on, EMP technology will go into fabrics to create smart digital clothing.

An Integrated Future

Our sense of touch and our ability to feel are integral parts of our existence in the physical world and play a fundamental role in daily life. As people begin to explore new, innovative ways to enhance user experience through devices that are increasingly in sync with our senses, new material technologies and products will become a way for manufacturers and designers to integrate haptic feedback in an effective, meaningful way.

Fig. 7: *The world's thinnest flexible keyboard with localized haptics and sounds is a product concept enabled with EMP actuators.*

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Exiting with Grace – and Profit

There are many ways to move on from the start-up phase. Some deliver a better return than others, as is explained in our fourth article in our venture capital series.

by Helge Seetzen

IT'S time to talk about the end. In previous articles, we discussed assembling a team, building a technology business, and financing it with investment capital. That's the fun part of entrepreneurship, but inevitably your venture needs to grow up. To do so, it needs to leave the start-up phase behind and, more likely than not, deliver an economic return for its stakeholders. In this article, we will talk about the concept of an exit, methods of achieving it, and the motivations of players involved in the process.

First of all, why would anybody want to "exit" the business they have diligently built over so many years? Isn't that a bit defeatist? To answer this question, it is important to understand that the term "exit," in the investment world, does not refer to people leaving the company. That might happen under a few possible scenarios, but investors are really talking about capital rather than people. And capital does need to exit in order to provide a return to investors and to compensate employees for their considerable efforts at salaries that are usually below market. Of course, many a founder will also be tempted by the lure of a bit of cash in their pocket. Exits are therefore about turning intangibles into tangibles – stock into cash.

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There are many ways to achieve an exit for your venture: acquisitions, asset sales, mergers, initial public offerings, talent acquisitions, and so forth. And for each of those outcomes there are countless strategies but few consistent rules. The latter is a limitation of the start-up environment. Starting a new company is really hard, and achieving a successful exit is even harder. Thus, there are only a very small number of people who have serial exit experience and practically nobody has lived through enough exits to speak with statistical authority about "exit strategies." The possible exceptions are fund managers and serial angel investors who might have seen quite a few exit deals, but mostly from the sidelines as, at best, advisors to the executive team.

Despite these limitations, there are some common observations about exit strategies to guide aspiring entrepreneurs on their journey. In this article, we will talk about the different types of exits and the motivations of the sellers. We will also share some tips toward realizing a satisfying deal.

Exit Types

As mentioned above, there are many exit scenarios, but some order can be found by arranging them in increasing value stages – much like the valuation steps discussed in the second article of this series on fund raising. From lowest to highest value – at least generally – we have the following exit types:

Liquidation: Most start-ups fail. So, regrettably, the most common exit is simply the dissolution of the business. Your creditors, including possible venture debt holders, will auction off your assets and the credit-card companies will take whatever is left. Dealing with a failed venture is a topic all by itself, but in the context of this article there isn't much further to be said about this exit type.

Asset Acquisition: It gets a bit more interesting if your assets are worth a meaningful amount to a buyer.[1] For technology ventures, that almost always means that a larger company would like to own your intellectual property without the hassle of buying the entire business. Often that is bad news for the seller, but an asset sale can be a success if the investment has been small so far. Good-quality patents can fetch hundreds of thousands of dollars each, so a small venture can have a successful exit after a modest seed round just by selling its patent portfolio (assuming it has one; this is more common for university spin-offs that start with a lot of patents but without

[1]Asset acquisitions, in the context of this article, are used to describe deals in which the assets are the only item of value to the buyer. In transaction terms it is perfectly possible that other types of acquisitions happen to also involve an asset purchase for financial reasons (*e.g.*, the acquirer might want to own the entire business of the seller – a "Revenue Stream Acquisition" in the context of this article – but do so by individually buying the assets and hiring the employees to avoid taking over the liabilities of the original company).

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significant financing). Asset acquisitions can also come in the guise of licensing deals, especially in industries like ours where a few big titans do all the manufacturing. An exclusive license paid by a lump sum is nothing but an asset acquisition by a different name.

Team Acquisition: One step up the value ladder is team acquisitions, often called acqui-hires in venture jargon. The buyer sees a high-quality team, possibly even with some relevant intellectual property, and wants to bring it all in house. This form of bulk hiring has become quite popular in competitive labor markets such as Silicon Valley, where Google, Facebook, and other tech giants routinely hire teams of 5–25 talented engineers under the guise of an acquisition. The employees and founders get continuous employment and possibly a small bonus, though most of their stock options are usually transferred to their new employer to ensure that they remain "locked in" after the acquisition. Investors usually make a small return, mostly to convince them to support the deal and waive the non-competition restrictions imposed on employees by the original company (this being the principal reason why the buyer cannot just hire all the staff individually).

Strategic Acquisition: Serious money starts to flow when the buyer sees strategic value in the start-up – witness the recent acquisitions of Instagram by Facebook and Tumblr by Yahoo for a billion dollars each. Strategic acquisitions of course also happen at lower price points, but all of them inflate value significantly above the tangible value of the assets and team. This intangible value boost, called "good will" in financial terms, represents the benefit that the buyer gets from the integration of the acquired business. Often these are just economy-of-scale benefits where the manufacturing or distribution capability of the buyer allows much higher value creation than the acquired venture can deliver on its own. Examples of other motivations for strategic acquisitions include elimination of competitive threats, protective intellectual property arrangements, accelerated time into a new market, and even branding exercises (the acquisition of Tumblr by Yahoo was arguably a successful $1 billion marketing campaign to signal that Yahoo is "hot" again). Strategic acquisitions, if timed right, maximize the value of technology and hustling while not yet incurring the risks associated with traditional business execution – thus representing by far the most numerous of the successful exit outcomes for technology start-ups.

Revenue Stream Acquisition: Some start-ups plunge into the world of traditional business execution, succeed in doing so, and actually turn a profit. Such companies are great opportunities for private or corporate equity investors who prefer to leave the execution of the business to the current team. They might integrate some aspects or shuffle the management a bit, but in essence they are acquiring a cash generator. For these deals the buyer will generally estimate the economic value of the business based on some form of discounted cash flow (*i.e.*, an estimate of how much profit the company will be making over the next 5–15 years, with appropriate discounts for risk and time value of money). Good private equity investors might also bring additional value to the company, but in essence this exit option is an exchange of current cash for more future cash. This works because of the time asymmetry of the involved parties. People age, corporations do not – so an offer of $10 million today for a business that stands to generate $20 million over the next decade might very well interest a founder while leaving plenty of upside on the table for the new corporate owner.

Initial Public Offering: During an initial public offering (IPO), the existing shareholders of a business sell some or all of their stock to the public – often represented by pension funds and other aggregators of public capital. This is the pinnacle of venture success – at least in current start-up culture. Once the bell rings, there are usually massive returns for investors, riches and ongoing employment for staff, and the status of modern-day saints for the founders. Unfortunately, IPOs are also by far the least likely outcome for start-ups due to the very high hurdle of needing massive revenue and/or broad public market hype. Moreover, a company will have ceased to be a start-up – in the sense of questing for a sustainable business model – long before the IPO formally recognizes this graduation with the imposition of regulatory and stock market pressures. Still, it remains an aspirational goal for many start-up founders.

There are numerous variants to the above exit types, but all exits have in common that shareholders have turned their intangible equity into tangible gains and that nothing will feel the same after the exit for any stakeholder. The magnitude of the former and impact of the latter mean that acquisitions become complex emotional affairs even before a buyer comes to the negotiation table.

Seller's Motivation

The type of exit encapsulates the motivation of the buyer, but what about the motivation of the seller? The three principal stakeholders of a start-up – investors, founders, and employees – usually have a shared motivation to reap an economic reward for their labors, but the timing and price that they might be willing to pay for this reward varies considerably. So, the first step toward an exit strategy is to understand the goals and motivations of your own stakeholders.

Investors: At first glance, investors have the most straightforward motivation – as much cash as possible for their investment. The story gets a bit more complicated when the dynamics of their investment fund are taken into account. In the last article, we looked at the compensation dynamics of venture capital fund managers and the way these can warp their economic perspective. This leads to a situation where the desire to generate significant cash is influenced by timing factors. Venture capital partners need to invest money and receive a return on that money in the time frame of their funds. On the investment side, they are constrained by the need to invest all the capital of their fund into a relatively small number of companies, as shown in "VC Investment" below. This situation creates considerable pressure for the VC, which will inevitably bleed over onto the company.

On the front end of the timeline, VCs generally dislike exit opportunities that occur before they have a chance to invest most of their capital into a venture – even if the opportunity itself might be quite lucrative (*e.g.*, an early exit offer might yield a 10× return on investment, but if the VC has only put in $1 million so far – out of a $250 million fund – then this just does not move the needle for them even if it might mean many millions for the founders and employees). Founders ignore this aspect of VC dynamics at their own peril. A boardroom drama that frequently occurs is an excited CEO presenting a great acquisition offer that would make everybody rich and even keep all the employees in the business – only to be reined in by the VC. Of course, the VC is not going to flat-out say that the deal doesn't make him enough money.

Instead, the typical response will be to paint the founder as a sellout who does not want to build a billion-dollar company (*i.e.*, one that can absorb a big chunk of money from the VC first…). In fact, this story line has become so much a part of start-up culture that few people understand the underlying self-serving interest anymore.

VC Investment

A typical 10-year VC fund might have five partners and $250 million under management for a 5-year investment period. In other words, they need to invest $250 million into companies in the first 5 years of their fund and then return a decent multiple on that money in the second half of the fund's lifetime.

Each partner can credibly sit on five Boards of Directors for their portfolio companies, so in the first 2–3 years, they will want to make about 25 investments – each capable of absorbing $10 million over its lifecycle (*e.g.*, a company might take $1 million as part of a Series A financing in the first year, another $3 million as part of the Series B a year later, and finally $6 million in the Series C growth round toward the end of the fund). Of course, some of these investments will fail before reaching the larger rounds, so the ideal investment opportunity for this example fund would be a venture that approaches them in the first or second year of the fund, takes $1–2 million then, and has the potential to take $10–$20 million if it reaches a Series B or C stage (more money than average to compensate for the failed ventures that did not take the full capital reserved for them).

Founders: Founders are not subject to the economic peculiarities of the venture capital model, but that does not mean that they do not have an agenda. It is just that theirs is usually driven by ego rather than economics. Most founders have to ask themselves at some point during their start-up career whether they want to be Caesar or Croesus – undisputed ruler or unimaginably rich. Start-ups offer a chance to become both, but not really at the same time. A desire to be Caesar – the ultimate boss who cannot be fired or gainsaid by anybody else – limits the scope of the venture, and thus its financial return, as it restricts the ability to bring in co-founders, investors, and strategic partners. Optimizing for economic gain therefore usually requires quite a few concessions on the control and power side of the start-up structure. Experienced founders tend to understand this trade-off and are usually more comfortable with performance-based structures (e.g., they remain king by virtue of high performance rather than some form of structural protection). Nevertheless, both types of founders exist and their preference will have a massive impact on viable (and available) exit options for the start-up.

Employees: With the exception of very early employees in high-growth ventures, most employees will not own enough stock to make truly life-changing returns in most exit scenarios. A common Employee Stock Option Pool will hold 10-15% of an early stage start-up with about two thirds of that going to senior executives and the rest being distributed among other employees. This puts the likely return of even a good exit in the same order of magnitude of annual compensation. As a result, employees generally are more worried about keeping their position than the cash payout of most exit scenarios. If you make $100K per year and the exit results in the loss of your position but with a $50K stock payout, that is just a termination with severance by another name.

Advisor Alignment

Advisors are a key part of most exits, whether they are lawyers, accountants, or investment bankers. Most advisors are paid by the hour, so their incentive is obvious. They need only a firm hand when it comes to the management of expenses. Brokers, in all forms, are a different story because at first glance their interests seem aligned with the company's stakeholders due to the commission nature of their compensation. Regrettably, that is not entirely true for two key reasons: First, brokers make nothing if the deal fails while the stakeholders still get to keep their company. Second, brokers start their investment on the first day of the negotiation while other stakeholders have often invested over several years. Combined, this motivates brokers to close deals as quickly as possible and essentially at any price – whereas other stakeholders might very well be comfortable holding out for better terms. This is a familiar feeling for anybody who has ever hired a real estate agent – their broker – only to feel pressured into a deal!

Engagement Process

Armed with a good understanding of the motivations of your stakeholders, it is time to set the exit plan in motion. By this time, you should have your team of advisors lined up. (See the sidebar, "Advisor Alignment.") The next thing to understand is that start-ups are bought, not sold. There is no such thing as an efficient market for start-ups. With the exception of a number of exceptional deals, every acquisition is ultimately a buyer-driven process based on an existing relationship. So the first step is to build those relationships.

As early as possible in your venture, you should identify the different types of future acquirers and what they might want from your business. Certain types of companies might value your team quite highly even if your technology is not a perfect match for them. Others will value your technology. And so forth. As an example, when we prepared the exit plan for BrightSide, my last venture focused on local-dimming LED TV, we classified three distinct categories of potential acquirers:

Licensing Companies: BrightSide had a broad patent portfolio and a strong engineering team. Both pieces would be a powerful asset for technology licensing companies that were trying to enter the display market. The value to them would be a ready-made team as well as the forward-looking revenue potential of our licensing deals (likely at a higher value than we were forecasting them internally, as the larger licensing company would have better leverage than a small start-up).

TV Manufacturers: At the time we had joint development projects with large TV manufacturers and were in licensing discussions with them. In addition to revenue sources, these were also potential exit opportunities with lump sum fees for the license being in the same order of magnitude as the company's valuation. A potential acquirer like this would care about the intellectual property and not much else.

Specialty Display Manufacturers: BrightSide made and sold high-end displays for niche applications. This was an early business, but we did hit seven digits and thus opened the door to a potential asset acquisition by a larger niche manufacturer (possibly including a team transfer as well –though usually such companies have a hard time integrating teams of 30–50 people due to their own relatively small size).

Maintaining Competitive Tension

Competitive tension is a key element of deal negotiation and often the only leverage available to the seller. Buyers are aware of this and most term sheets contain a no-shop provision that prohibits the seller from continuing negotiations with third parties. It is very difficult to avoid such limitations, but tension can still be maintained through indirect competition: your team might pursue a venture capital investment or a major technology licensing deal in parallel to the acquisition negotiation. Neither would be prohibited by a no-shop agreement but both are usually an effective competitive threat. As a recent example, the $50 million VC investment into Instagram just a few days before its acquisition by Facebook was most likely not a "get rich" scheme by insiders but rather exactly such a manufactured indirect threat to the acquisition.

The next step is to identify prospects in each category and build initial relationships. These relationships should be continuous and, initially, not focused on the exit at all. Nobody likes salesmen, so start by forming professional bonds, ideally at different levels of the organization. Your first priority is to identify a champion within the organization that can help you through the process and ultimately advocate for your venture within the acquirer. If possible, try to also establish relationships between the engineering teams on both sides. Engineers do not make acquisition decisions by themselves, but they will almost certainly be asked by management at some point in the acquisition process about your team – making engineer-to-engineer relationships invaluable.

Relationships are formed over time, so the best path here is to establish a repeating pattern of engagement. For some acquirer types there might be an opportunity for a formal business relationship prior to the acquisition – such as a joint development project – but for others this can just take the form of going for lunch every 6 months for an update. If possible, try to identify a value-added purpose for the engagement: collaboration at standards meetings like ICDM; meeting up at conferences such as Display Week; joint talks or other presentations such as Display Week Seminars; contributions to open source software projects; participation in the Display Week Program Committee or governance of the Society; and so forth.

Once the relationship is formed, the next step is to explore the appetite of your potential partner for different types of deals. Some of this can be found in the public domain, such as the company's recent acquisition pattern, but a lot requires dialog with your new connections. Are they hiring? Are there strategic areas identified for expansion? Are their engineers busy on high-priority projects or looking for work? Are they hiring or downsizing? Questions like these provide the canvas on which a good acquisition strategy can be drawn.

Team Involvement

Opinions differ on when a CEO should bring a team into the acquisition dialog. Involving them early allows better distribution of the engagement workload, while a later involvement will keep the team focused on the core business for as long as possible. Regardless of your choice, your team will eventually know almost everything about an emerging deal, especially at the senior levels. With that knowledge, the dreams and fears will start to spread: Dreams of getting rich, fears of losing their jobs, since many acquisitions include staff reductions (ironically, the employee functions that would be the most involved with the exit transaction, such as finance and HR, are also often the first functions to be eliminated post-acquisition – causing a difficult misalignment of interest within the exit team of the start-up).

Fears are obviously damaging, but the impact of dreams can be even more corrosive. Two of my worst professional experiences were trips home from deal meetings that fell apart at the very last minute (once literally during the final signature meeting). This happens, and it can absolutely devastate the morale of a company if not managed properly. If at all possible, try to only involve those team members who can handle, emotionally and professionally, the ambiguity and uncertainty of strategic negotiations.

With a good relationship and understanding of a company's needs in place, the discussion will eventually turn to the topic of a partnership or acquisition. Start by exploring the practical boundaries of a possible engagement – what do they want and what do you want? You might need to bracket a price range to make everybody comfortable, but definitive price negotiations usually come later in the process. First, the buyer will want to conduct some amount of informal due diligence, usually by visiting your company, meeting the team, and otherwise digging into your business. This is probably the most delicate period of the acquisition process, full of opportunity to distract your team and possibly causing fatal morale issues (see the sidebar, "Team Involvement"). At this point, you may also want to give some consideration to the concept of competitive tension (see "Maintaining Competitive Tension").

This period usually ends with the development of a term sheet – a document that, as the name implies, lists the principal terms of a future deal (*e.g.*, price, deal dynamic, team transfers, *etc.*). A good term sheet is usually the end of the process in terms of negotiation risk, at least if there are not too many skeletons buried in your corporate closet. (For more on term sheets, see the second article of this series, "Raising Capital for Technology Ventures" in the September/October 2013 issue.) Given the finality of the term sheet, this is definitely not the time to be stingy with advisors. Bring in the lawyers, accountants, and other specialists – any structural problems at this stage can be hard to fix later (do not forget to get good tax advice, as different deal structures can have a massive impact on personal wealth gain for founders, even with an identical purchase price).

A Word on Price

Deal pricing is both an art and a science. The corporate development team of the buyer will usually generate lots of spreadsheets with budget forecasts and discounted cash flow calculations (estimating the value of the forecasted revenue of the acquired business). Whether their management team ultimately uses all that information is a different story and, in any case, outside of your control. Your best hope to influence the pricing process is to establish a strategic rationale for the deal (and coach your champion on how to present it), keep your key assets clean and easy to understand (*e.g.*, intellectual property), and highlight the synergy benefits of the deal. Deals ultimately come down to the eagerness of the decision makers on both sides, so a good narrative is more important than any financial spreadsheet.

Due Diligence

The final stage of the process is due diligence. In addition to the development of the final full agreement, based on the term sheet, the buyer will send a horde of experts to poke into all parts of your business. You will inevitably be outnumbered, usually just by the lawyers alone, and the buyer will unfortunately control the process almost entirely. It is therefore critical that you clearly understand the goal of each due-diligence activity and steer as quickly as possible to the relevant check on their list. While some competitive pressure is good, try to avoid salesmanship and instead focus on closing out open issues – at this stage it is no longer about impressing them with the quality of your code but rather about showing them as efficiently as possible that no third-party software sits in your system (and the best way to achieve that might just be to delete your entire repository except the very latest code version…). Checks, not sales.

While all of this is happening, you can turn what little mindshare you have left toward the topic of integration. Will your team get absorbed on day one or gradually integrated over the course of the first year? Try to find relevant counterparts in the buyer's organization for all your key leaders so that they can start the process of knowledge transfer. Apart from being good form to make the integration as smooth as possible, there is often also an economic incentive to do so (*e.g.*, most deals leave 10–25% of the payout in escrow for 12–24 months to ensure against any problems that might arise).

Eventually, the lawyers will have billed as much as they can get away with, management will become impatient, and enough checks will show on the list – closing day is at hand. The final agreement will be signed by both sides, your shareholders will cast any necessary votes (you did make sure that they are all aligned, right?), and money changes hands. In addition to a good chat with a personal wealth advisor, this would also be an opportune time to take a long vacation and re-acquaint yourself with your spouse, who has likely not seen much of you for several months.

The next article in this venture capital series looks at a more specific area of venture capital: the issues surrounding technology transfer for university researchers. ■

Third-Annual I-Zone Call for Papers

The Innovation Zone (I-Zone) at Display Week is one of the most exciting places on the show floor. Nowhere else in the world will you see, in one location, so many prototypes and discoveries that will change the future of the display industry in years to come. Two recent examples are a new film-type plasma display that rolls up like a windowshade from Shinoda Plasma Co., Ltd., which won a 2013 Best Prototype Award, and a microfluidics-based technology that enables transparent physical buttons to rise up from a touch-screen surface from Tactus Technology, which won in 2012.

On June 3 and 4, at Display Week 2014 in San Diego, California, the Society for Information Display will once again host the I-Zone, a forum for live demonstrations of emerging information-display and display-related technologies. The I-Zone, which is sponsored by E Ink, offers researchers space to demonstrate their prototypes or other hardware demo units for two days free of charge at the premier display exhibition in North America. The committee is actively encouraging participation by small companies, start-ups, universities, government labs, and independent research labs.

Proposals to demonstrate new displays, input technologies, and innovations in related fields such as lighting and organic electronics are now being solicited. Technologies should be in the pre-product stage, and demos that will be shown for the first time in a public forum at I-Zone are especially encouraged. Submissions are due by March 1, 2014.

To submit your proposal, please visit http://www.sid.org/About/Awards/IZone.aspx. For any questions related to the 2014 I-Zone, please contact Professor Jerzy Kanicki at kanicki@eeds.umich.edu.

SID-Mac Meeting Features UHD

The difference between UHD and 1080p TV imagery was one of the topics addressed by Claudio Ciacci, Test Program Leader for Video at Consumer Reports, at a special presentation for the Mid-Atlantic Chapter of the Society for Information Display in Yonkers, New York, last fall. According to Ciacci, UHD does offer a better picture than HD, but the differences may be not be so apparent in typical home-viewing situations, and lower prices and more content will be necessary to make these sets more appealing to the average consumer. For more on UHD and 1080p, see his blog at: http://www.consumerreports.org/cro/news/2013/10/ultra-hd-vs-hd-tv-is-ultra-worth-the-extra-money/index.htm. Ciacci also gave a brief overview of TV testing procedures at Consumer Reports and reported on LCD/LEDs, plasma, and OLED TVs.

Also presenting at the meeting was Evan Donoghue, Thin Film Scientist at eMagin Corp., who reported on EuroDisplay 2013. He focused on OLED advances at EuroDisplay, as well as advances in other materials that would affect OLED microdisplays. Matt Brennesholtz, a Consultant and Senior Analyst with Insight Media, discussed advances in projection technology that had occurred since Display Week 2013 in Vancouver. He focused on projectors with solid-state illumination, including lasers, LEDs, and hybrid systems.

– Jenny Donelan

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To be fair, most of us will still prefer to view content on a flat screen. Think of the old days of reading the newspaper and "fluffing it out" to make it flat so you could read it. Who wants to have to mess with a display like that? However, the opportunity for stretchable, conformal, and flexible display technologies is significant once they can provide the performance desired for wearable use, or the low cost required for applications such as smart packaging. The authors for this issue will hopefully inspire all of us to continue taking steps toward that ultimate goal of ubiquitous displays: when displays are able to disappear into the surfaces and products we encounter each and every day. ■

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has been doing for eons. I'm sure you will enjoy this article and we are very grateful to the authors for working with us.

Our next Frontline Technology feature, titled "Intrinsically Elastomeric Polymer Light Emitting Devices," by authors Jiajie Liang and Qibing Pei, examines the research work conducted at UCLA to develop transparent flexible polymer OLED (PLED) displays that can not only be rolled up but can, in fact, tolerate being stretched thousands of times and still retain their essential functional properties. These are high-luminance PLED displays on flexible and stretchable conductive backplanes that very nearly mimic human skin-like properties but also include transparency. This is very interesting and significant work that deserves recognition – I'm pleased we were able to bring this to you.

And while we're discussing "skin," we also have a very interesting Frontline Technology story exploring various materials and flexible electronic structures to produce what the authors refer to as "Imperceptible Electronic Skin." Reporting on a variety of recent achievements at the University of Tokyo, authors Tsuyoshi Sekitani, Martin Kaltenbrunner, Tomoyuki Yokota, and Takao Someya talk about their vision for artificial electronic skin that can be used either for robots with human-like senses or for prosthetics on humans that can extend our current abilities to feel and sense our environments. I'm sure you will find their work both interesting and thought provoking as well. It reminds me again of so many times when I feel like science and science fiction are converging.

Our cover story, along with the following two features I introduced, were all developed for us this month by our Guest Editor Jason Heikenfeld. Jason is a frequent contributor to *ID* and his insight and imagination are highly valued here. Once again, we thank him for his efforts and encourage you to read his guest editor's note, "On the Frontlines of Innovation: Inspiration for 'Skin-Like' Displays."

Our Display Marketplace feature this month comes from Veronica Thayer, who is a consumer-electronics and technology analyst for IHS. We are very excited to have IHS on board with *ID* as another member of our contributing analyst team. It is through the generosity of their efforts that we are able to present a snapshot of the business side of displays each month. In this month's feature, "Fewer U.S. Consumers Interested in Buying New TVs," Veronica talks about the ups and downs of this marketplace, and the shift from conventional TVs for viewing broadcast content to smart TVs and so-called "second-screens" like tablets, and the growth of on-demand Internet streaming content. One thing I found particularly interesting in her report was that the percentage of consumers purchasing a TV in the past year was nearly twice as high among tablet owners. Also, tablet owners showed a clear preference for bigger screen sizes, with 49% of tablet owners preferring a 40–49-in. screen size. To me, this says that the traditional fear of second screens eroding the TV market is probably not true but, in fact, a variety of other much more complex dynamics are actually at work in this marketplace. Still, it's a tough market out there and at the time of this writing we do not yet know how the holiday season sales are breaking down.

Turning to the subject of OLEDs, we have our next Frontline Technology feature, "Applying OLEDs in a Manufacturing Process," contributed by Kai Gilge, Ansgar Werner, and Sven Murano from Novaled. In this feature, we learn about the important considerations for display manufacturing with OLED materials and some of the key process parameters that must be understood to achieve good success. We like to hear about about the manufacturing aspects of OLED technology, so I was very pleased when we saw this article proposal come our way.

Another interesting application that is driving demand for advanced materials research is haptics technology. Defined by our friends at Wikipedia as "… any form of non-verbal communication involving touch," haptics really encompasses all those important considerations when you create real-life user interface devices such as the audible and physical feedback of a keyboard and the feel of the environmental controls on the dashboard of your car.

Smartphones and tablets require a smooth front glass surface, which severely limits the types of physical feedback mechanisms you can achieve when using the virtual keyboards. However, recently, companies have begun developing methods to augment that front surface and the most recent effort involves something called Electro-Mechanical Polymers (EMPs), which are described this month in our Frontline Technology feature titled "New Electro-Mechanical Polymer Actuator Technology for Better Interactivity" from Dr. Christophe Ramstein and Ausra Liaukeviciute from Novasentis. These new materials allow the user to feel tiny local vibrations, simulating the tactile response of a mechanical keyboard. They can be used in a variety of applications that may eventually include transparent touch screens.

These two features on OLEDs and EMPs were developed for us by our guest editor Ion Bita, who talks about the landscape of materials research in his guest editorial, "Momentum for Materials." As Ion notes, both OLED and touch-technology applications are significant drivers for further materials research and development today. We thank Ion for his great effort in bringing these features to us for this issue.

We are pleased once again to bring you another chapter in Helge Seetzen's continuing saga on how to get rich quick with your own startup company. OK, so if you have been reading this series so far you know that's not even close to what he's really saying. The process of creating a technology company, getting venture capital funding, building a successful technology business, and nurturing it to maturity takes extreme dedication, careful planning, lots of luck, and assistance from many seasoned professionals. This month, Helge explores that long sought-after and highly elusive goal, "Exiting with Grace – and Profit." It's not easy, but it is possible under the right circumstances to actually make a profit and move on from your venture with something to show for all your hard work. I'm sure you will find this latest installment another exciting part of this great series.

And so, as the holiday season winds down and we start to look forward again, I wish you all the very best personal and professional success in 2014. ■

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from discrete touch panels to thinner, more integrated configurations, including sensors patterned directly on chemically strengthened protective glass covers and display panel integrated touch sensors (such as on-/in-cells for LCDs).

With so much activity directed at improving touch-input interfaces, we are delighted to include an article that focuses on developing complementary materials and devices enabling touch-output interfaces. Also known as haptics, tactile feedback in mobile devices is an evolving field currently dominated by zero-dimensional architectures (whole-body device motions induced by electromagnetic motors). The authors, Christophe Ramstein and Ausra Liaukeviciute of Novasentis, Inc. (U.S.), a company known until recently as SPS, Inc., describe the use of electroactive mechanical actuator films for the next generation of haptics with spatially localized feedback. In particular, the properties and benefits of electromechanical polymers are examined, with a focus on ferroelectric fluorocarbon polymers capable of piezoelectric or electrostrictive responses to applied electric fields. These relatively thin film actuators were shown at Display Week 2013's Innovation Zone (I-Zone) and have recently garnered the Novasentis team the 2014 CES Innovations Design and Engineering Award in Embedded Technologies.

We hope you will enjoy reading these articles along with the rest of this issue.

References

[1]For example, see the March/April 2013 issue of *Information Display* magazine and the 2013 *SID Symposium Digest of Technical Papers*.

[2]See Nanosys/3M's QDEF and QDVision's ColorIQ quantum-dot technologies, both recipients of the SID's Gold Display Component of the Year Award (in 2012 and 2013, respectively) and both shipping in volume (*e.g.*, QDEF in the new Kindle Fire HDX 7-in. tablet and ColorIQ in the new Sony Bravia line of LCD TVs).

[3]H. Uoyama, K. Goushi, K. Shizu, H. Nomura, and C. Adachi, "Highly efficient organic light-emitting diodes from delayed fluorescence," *Nature* **492**(7428), 234–238 (Dec. 2012).

[4]For example, see the July/August 2013 issue of the *Information Display* magazine and references therein.

Ion Bita *is Senior Staff Engineering Manager at Qualcomm MEMS Technologies in San Jose ,California, were he currently works on reflective displays, front lighting, and projected-capacitive touch screens. He is a Senior Member of the SID and currently serves as Chair of the Display Manufacturing Program Committee for SID 2014. The opinions expressed in this article are his own and do not reflect the opinions of his employer. He can be reached at ibita@qmt.qualcomm.com.* ■

Display Week 2014 Networking Events

June 1–6, 2014

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 2 at the San Diego 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 4. 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.

Special Networking Event, Wednesday:
This year's event will be held aboard the aircraft carrier and museum the USS Midway, located in the San Diego harbor near the convention center.

Henkel is graciously sponsoring this event, which will include a light meal of drinks and appetizers.

president's corner

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SID also continues to work hard to deliver meaningful, high-quality conference events to provide learning, networking, and commercial opportunities for SID's members. I hope you've had a chance to take note of the professionalism and upgrading of SID's annual conference, Display Week. We received a great deal of positive feedback regarding Display Week 2013 in Vancouver. Display Week has always been the best place to go to learn about displays, including fundamental technology instruction in short courses and seminars and reports on new technology developments in the Symposium. The SID Program Committee continues its efforts to maintain high standards for paper acceptance and to attract the strongest possible technical presentations to Display Week, including solicitation of key researchers who might not otherwise be inclined to publish their results.

We have also been working hard to upgrade the Display Week exhibition. It is important that Display Week be recognized not only as a research or technology conference, but also as a place where companies can go to do business. All attendees want to see the latest displays and input technologies, so the exhibition is important to SID, but SID's leadership also recognizes the need for corporate participants to achieve return on their investment. To be effective, simply stated, customers and providers need to have an effective forum to meet, and the conference needs to promote commerce. To improve participation, we are focusing future venues on accessible locations on the west coast of North America. We have given renewed emphasis to SID's annual Business Conference, the Investor's Conference, and Market Focus Conferences, and we have been upgrading the exhibition as a place to connect customers, display makers, component makers, and service providers. Among other benefits, Display Week provides a very favorable climate for meeting key system integrators, most of whom are based in North America and many in Silicon Valley itself. We will continue our efforts to make Display Week the gold standard of conferences for our field.

Finally, significant work continues behind the scenes to provide better member services. We recognize the need to improve the customer IT experience and that project is under way now. Please know that SID is here to serve you, our membership. We will continue to innovate within SID so that we can better serve your needs and help the display industry and academia thrive. ■

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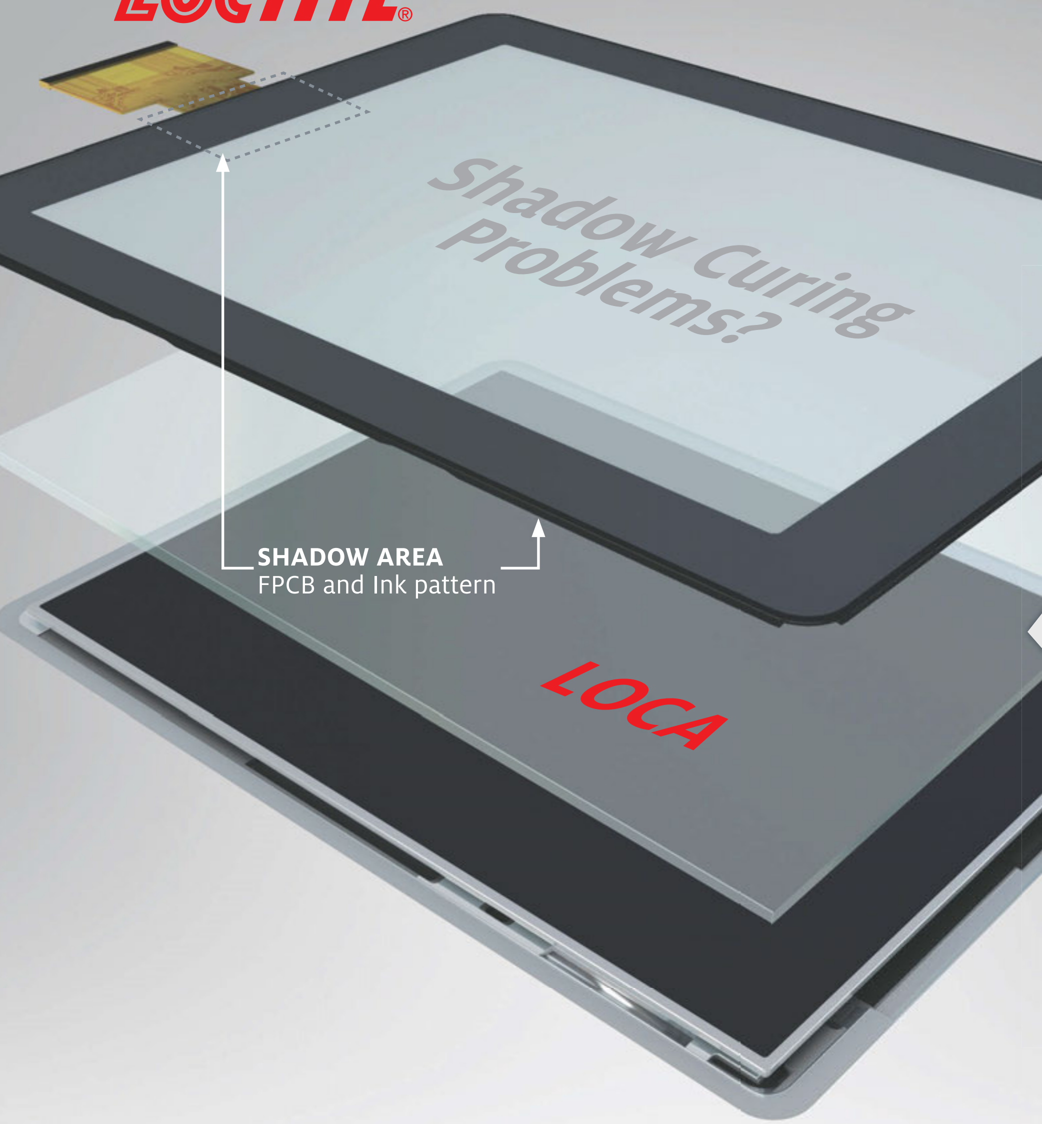

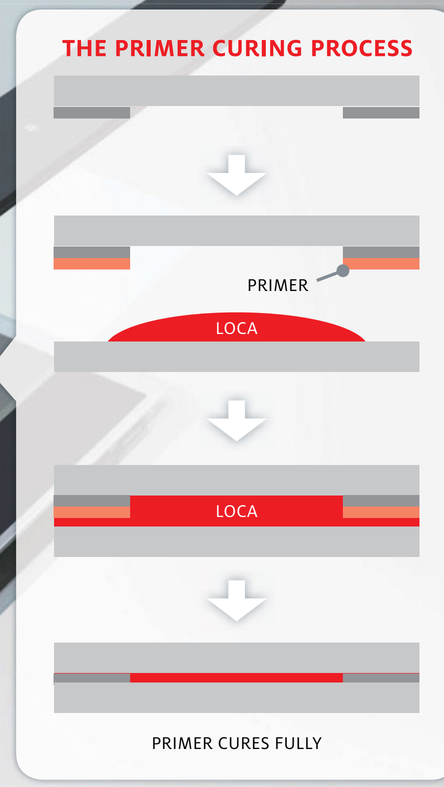

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