TABLETS AND INTERACTIVITY ISSUE

Information DISPLAY

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The Next Interface Evolution: Natural and Intuitive

TABLETS AND HANDHELDS ADVANCE MEDICAL IMAGING

FROM GREAT IDEA TO SUCCESSFUL BUSINESS

TABLET TECHNOLOGY SHOOT-OUT: WHO WINS?

Plus

Direct Dry-Film Bonding

Challengers Take on ITO

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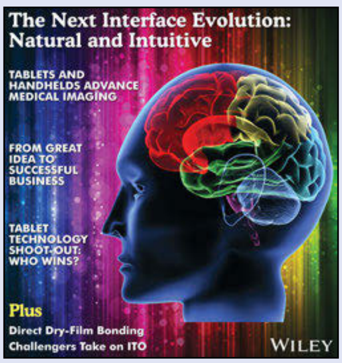
ON THE COVER: *Key natural user input technologies that are behind the emerging multi-modal interaction paradigms are paving the path to an era of perceptual computing and a new class of highly interactive applications and user experiences.*



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In the Next Issue of *Information Display*

Lighting and Display Week 2013 Overview

- OLEDs for Professional Lighting
- LED Lighting Comes of Edge
- Display Week 2013 in Review
  - LCDs
  - Flexible Displays
  - Interactivity
  - OLEDs
  - 3-D
  - Best-in-Show Awards
  - I-Zone Prototype Award Winner

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contents

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editorial

Finding Balance When Commitments Heat Up

by Stephen Atwood

It's mid-summer up here in North America and for most of us the pull of family and outdoor activities competes with the necessities of our professional activities. While the pressure of getting new products released and growing your business continues, the summer brings that extra challenge of making time for recreation, scheduling family vacations and taking advantage of those fleeting moments when you really can't convince yourself that it's "just as well" to be locked inside working.

Finding the right balance is not easy. Work deadlines loom, opportunities are fleeting, and there is always another problem to solve. However, I believe we are all better off when we can walk away for a while to recharge and enjoy the many other things life has to offer. In the interest of full disclosure, I did start working on this editorial from my campsite at a nearby lake, but I did not finish it there. After I got about half way through, I took my own advice and went swimming and fishing for the rest of the day. The editorial and the rest of our July/August articles were still there when I got back from the lake, and then it was time to put them into a great issue for you to enjoy.

We begin the July/August issue with the subject of user interfaces. Everyone knows what they are, what they like about them, and what they don't. Despite lots of research and conceptual demonstrations, as well as some intriguing Hollywood fabrications, the ways that all of us interact with our computing devices has not changed much in many years. Yes, touch and recently multi-touch interfaces have become more mainstream, but it all still involves our hands or fingers and a physical contact with some button, mouse, or flat surface. While there have been some promising demonstrations of late using speech, head/eye tracking, and gesture detection, most have involved specialized platforms that are a long way from mainstream adoption. Earlier this year, I was privileged to attend a one-day SID conference in San Jose and hear Achintya Bhowmik, the Director of Perceptual Computing at Intel Corporation, talk about his work at Intel to bring these types of new interaction paradigms to modern commercial computing platforms. We asked Dr. Bhowmik to expand on his talk and develop a Frontline Technology article providing specifics on how these new interface paradigms work and what the next steps would be to implement them on the commercial platforms we all utilize today. The result is our feature article, "Natural and Intuitive User Interfaces with Perceptual Computing Technologies." I'm sure you will be as excited with the prospects of this work from the Intel team as I am.

A Growing Market Segment

While somewhat new to the scene of portable computing devices, tablets have quickly grown to fill a critical market segment. They enable lots of uses due to their screen sizes that are larger than smartphones and their much lighter weight and better battery life than laptops. Our guest editor this month is Russel Martin from Qualcomm. Russel has been a widely respected colleague in the display industry for many years and is currently the director for sensor technology at Qualcomm. Russel has arranged for two great articles for us and he sets the stage for them in his Guest Editorial, "Tablets' High Performance Sends Them Off to Work." The first Frontline Technology article,"Tablet Display Technology Shoot-Out," is written by well-known author and technology analyst Raymond M. Soneira. It provides a detailed and thorough

(continued on page 43)

Peratech Touches Up QTC

Peratech, based in Richmond, England, recently launched the QTC Ultra Sensor, a touch-screen technology for OLED phone, monitor, and large, interactive displays (Fig. 1). Peratech claims that the new technology is so sensitive that it can detect finger touches on the front of the display when it is placed behind the OLED panel. The benefit to this is that having the touch-screen sensor behind the display allows more light to get through and thus enables a longer battery life.

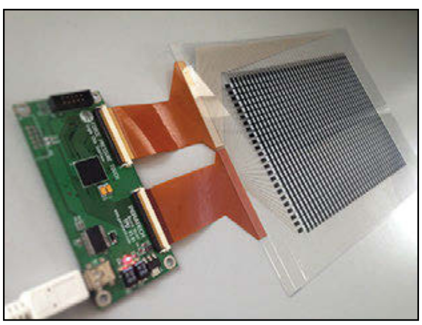

Fig. 1: *The QTC Ultra Sensor touch-screen technology from Peratech is designed for OLED displays and works even when placed behind the OLED panel.*

The new QTC Ultra Sensor technology is a follow-up to Peratech's QTC Clear touch-screen technology that was launched in 2011. QTC stands for Quantum Tunneling Composite, which is a relatively new approach to force sensing. It is made from a polymer with nanoscale conductive particles. The particles have spikey surfaces from which electrons "leap" from one to another when a force such as pressure is applied. *Information Display* featured QTC in a Technology Preview in the January 2012 issue.

QTC is not currently being used in commercial display products, but QTC textile switches are already in use in about half a million high-end sport and ski jackets for controlling phones and I-pods in pockets. On the display front, Nissha has been working on using QTC in the front of displays (the two companies signed a licensing agreement in 2010) and several companies are currently evaluating the new behind-the-display technology, according to a Peratech spokesperson.

Amazon Buys Liquavista

In the weeks leading up to Display Week last May, news broke that Amazon.com had acquired Liquavista from Samsung Electronics Co. Liquavista, a company based in The Netherlands, has patented electrowetting technology that has for some time been considered a contender for color e-Readers. Neither firm has had much to say about the transaction (and neither responded to inquiries from *Information Display*), but Liquavista is now listed as "An Amazon company" on the Liquavista Web site. Samsung bought Liquavista in early 2011 for an undisclosed sum, and the price paid by Amazon has not been disclosed either.

The obvious-seeming conclusion is that Amazon will use Liquavista's technology to finally produce a color e-paper product. But some commentators have questioned why Samsung would sell the technology if it was ready to be implemented in products. The answer may be that Amazon is more committed to e-Readers than Samsung, now that the e-Reader market has settled and even shrunk.

Paul Semenza, Senior Vice-President with NPD DisplaySearch, had this to say: "It was not clear to me whether Samsung acquired Liquavista [in 2011] to build e-Readers or to add to its display technology portfolio. For Amazon, one scenario could be a good-better-best strategy – the monochrome E Ink device, a color device with Liquavista, and the [LCD-based] Kindle Fire, which is moving to high resolution. The challenge is the price – unless Amazon starts giving away the E Ink devices, there is not much room between those and the Kindle Fire, and the cost of the Liquavista displays may be high, if only because Amazon is the only customer."

Neater Nanocrystals

Pixelligent Technologies, which makes nanocrystal additives for the electronics and semiconductor markets, recently announced PixClear Zirconia nanocrystals. When incorporated into existing products, these nano-additives can increase the light output and readability of touch screens and displays. PixClear also increases the light output of products for lighting applications such as HB LEDs and OLEDs (Fig. 2).

Pixelligent was developed to address the problem of nanocrystal dispersions that can suffer from aggregation and cloudiness and are unstable and difficult to process, preventing their commercial adoption. According to Pixelligent, its dispersions are completely clear and enable precise control over target applications' optical, chemical, and mechanical properties.

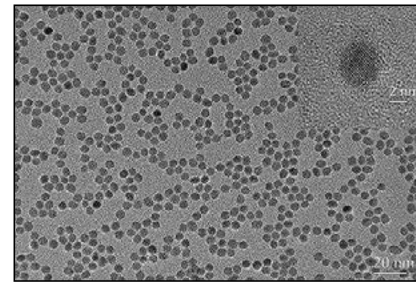

Fig. 2: *A typical TEM (transmission electron microscopy) image of PixClear shows spherical nanocrystals with 5 nm size and narrow size distribution.*

Dispersion technology is a critical enabler for the manufacturing of very-high-quality nanocomposites used in a wide range of applications, including touch screens, OLEDs, and CMOS image sensors. Pixelligent's PixClear nanocrystal dispersions have been tailored to be compatible with a wide variety of monomers and polymers. Its patent-pending synthesis and surface modification technology produces high-quality dispersions that can be incorporated into many of the most widely used polymer systems. This enables highly transparent formulations with nanocrystal loadings in excess of 80% weight, while reaching a refractive index as high as 1.85. Additionally, PixClear provides great flexibility for index matching of dissimilar materials.

Holographs Evolve

According to a recent article in the June issue of *Nature*, new modulators for holographic video displays are being tested that should enable better holographs, and even color ones. The paper's authors, one of whom is V. Michael Bove, who wrote about holographic research in the article "Holographic Television at the MIT Lab," in the November/December 2012 issue of *Information Display,* suggest that this technology can be used as a platform for low-cost, high-performance holographic video displays.

– Jenny Donelan

guest editorial

Tablets' High Performance Sends Them Off to Work

by Russel A. Martin

In the past few years, the emergence of tablets has driven yet another spurt of growth in the display industry and in its range of products. At this point, roughly one quarter of the U.S. population owns a tablet, e-Reader, or related product. The dominant use of these products is by consumers accessing information: reading books, viewing photographs, reviewing documents, checking e-mail, and inspecting Web sites. But success in the consumer world has driven adoption of tablets in a range of other areas, including educational, industrial, military, and medical. The viewing-heavy focus of tablets makes the display the critical element of the system. We see this in the display-forward marketing of tablets in which resolution, color gamut, and diagonal size dominate product feature lists. Can you think of a tablet marketed for its processor speed or configuration?

In this issue of *Information Display*, there are two articles that discuss tablet performance. Ray Soneira leads us through a range of quantitative measures of display performance and careful comparisons. He has judiciously picked four representative tablet displays to compare in detail, with LCD and OLED technologies both represented. More importantly, he discusses the tradeoffs, compromises, and missteps in the design of tablet (and phone) displays. Significantly, he demonstrates how strongly performance is controlled by ambient lighting. The extra mobility afforded by tablets makes this a significant issue in a way similar to that for mobile phones.

Aldo Badano shows us what is important when one applies tablets to the medical world. (I do not want an operation to remove a bad pixel from my kidney.) He compares the performance of handheld displays to those of medical workstations, showing us when the mobile device can play a similar diagnostic role. Using an analysis of gray scale, resolution, spatial noise, and ambient reflections, he compares device performance. Not surprisingly, he finds problems with reflections similar to those pointed out by Soneira. While the tasks done on tablets in a medical setting are different from those in the commercial or consumer space, in the end, the image-quality requirements are set by the limits of human vision. Doctors, artists, engineers, and students all look at tablets with two eyes and need to pick out the critical details.

My expectation is that the variety and uses of tablets will expand well beyond their current focus in the consumer space. When access to information is the primary goal of an information appliance, then tablets are the natural choice. Data entry is not as easy as on a computer with keyboard and mouse, but for many operations, the difficulties can be overcome with well-designed user interfaces. Outside of general consumer use, there are varying requirements for tablet displays and tablet design. As Badano explains, uniformity and color consistency are requirements for medical applications. In hospital settings, a mechanical design that allows easy wipe-down for sterilization would be an advantage, as might an anti-microbial screen surface. In industrial settings, durability and an easy way to grip the tablet are strong design considerations. For the military, sunlight readability would be a valuable feature. If that readability came from a reflective display, then a smaller battery could be used. That might ease some of the soldier's burden of lugging around 7 kg of batteries. Education faces yet another set of challenges, cost being the primary concern, but closely followed by the need for robustness in constant use.

Enjoy Soneira and Badano's articles on tablet display performance. Afterwards, think about how tablets are finding their way into more and more applications. What requirements will they need to meet to succeed in the next application? ■

Natural and Intuitive User Interfaces with Perceptual Computing Technologies

The ways we interface and interact with computing, communications, and entertainment devices are changing. A transition to natural and intuitive user interfaces promises to usher in a new class of exciting and immersive applications and user experiences.

by Achintya K. Bhowmik

HUMAN–COMPUTER interaction and user-interface paradigms have been undergoing a surge of innovation and rapid evolution in recent years. The human interface with computers has already been transformed over the past decades in a major way, with graphical user interfaces that employ a mouse as the input device replacing the old command line interfaces based on text inputs. Touch technology has coincided with many breakthrough advances in mobile-display technologies toward power-efficient, thin, and light devices with stunning visual performance.[1] We are now witnessing the next interface evolution, with the advent of more natural user interfaces in which the user interacts with computing, communications, and entertainment devices using gesture, voice, and multimodal inputs, as well as touch.

These new interface technologies and the ensuing applications present exciting opportunities for the display technology and consumer-electronics industry at large. This article outlines the key technologies, recent developments, and trends toward realizing natural user interfaces and implementations of new interactive systems and applications.

Achin Bhowmik is the Director of Perceptual Computing at Intel Corp., where his group is focused on developing next-generation computing solutions based on natural human–computer interaction technologies, intuitive interfaces, immersive applications, and new user experiences. He has taught graduate-level courses on computer vision, image processing, and display technology. He has more than 100 publications, including a book and 25 issued patents. He can be reached at achintya.k.bhowmik@intel.com.

Touch Inputs

The recent transformation of the display subsystem from a visual information device to an interactive one is largely due to the integration of touch sensing to the display module. With the capability of sensing contact locations on its surface, a display device morphs from a one-way interface device that merely shows visual content to a two-way interface device that also directly receives user inputs and thus enables interactive applications. It took decades of development after the first report of capacitive touch screens, by Johnson in

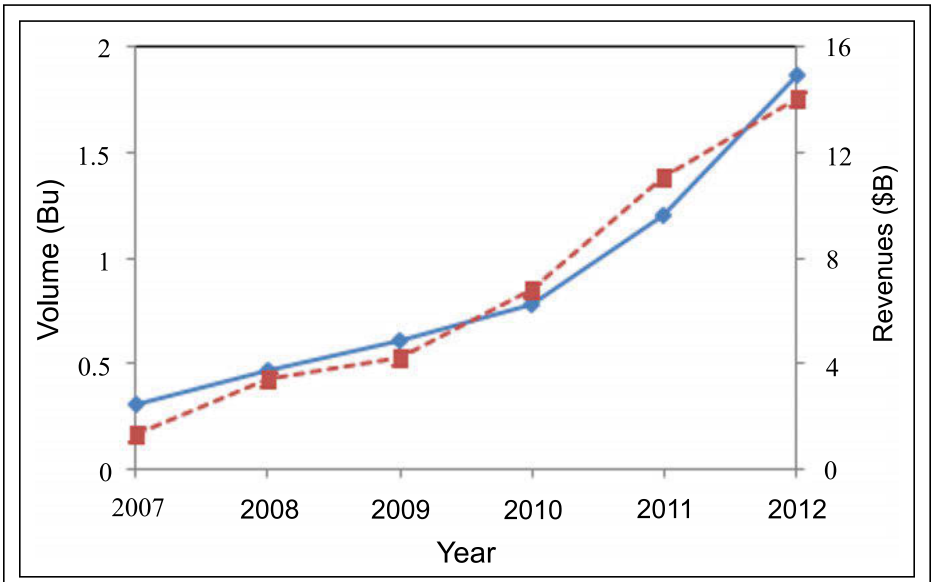

Fig. 1: *Overall touch-screen market growth from 2007 to 2012 is depicted by unit volume in a solid line on the left axis and revenues in dashed line on the right axis. Source: DisplaySearch.*

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1965,[2] for the technology and usage to go mainstream with consumers. Recently, touch-screen technology and its commercial deployment have been undergoing a phase of fast adoption and growth, thanks to the widespread proliferation of smartphones and tablets. Touch-enabled display screens are increasingly appearing in modern laptop computers, especially in the category of ultrabooks.

Let us take a quick look at the market size to gain appreciation for the footprint of touch-screen technology. The industry now ships well more than a billion units of touch screens per year. As shown in Fig. 1, the market for touch-screen technologies has grown at a rapid pace recently, both in terms of total units and revenues.[3]

While projected-capacitive technology has been the main enabler of touch penetration in consumer devices in recent years, other technologies for sensing contact location on the surface of a display include analog resistive, surface capacitive, surface acoustic wave, infrared, camera-based optical, LCD in-cell, bending wave, force-sensing, planar scatter detection, vision-based, electromagnetic resonance, and combinations of technologies.[4]

Multi-Modal Inputs: Toward Perceptual Computing

We human beings use multi-modal interface schemes to comprehend our surroundings and communicate with each other in our daily lives, seamlessly combining gestures, voice, touch, facial expressions, eye gaze, emotions, and context. We have evolved into highly interactive beings, aided by a sophisticated 3-D visual-perception system, aural and auditory capabilities, skin with tactile sensitivity, and other perceptual sensors. Well more than half of the human brain is dedicated to processing perceptual signals,[5] which enables us to understand the space, beings, and objects around us and interact in contextually aware natural and intuitive ways. As depicted in Fig. 2, the human-visual system consists of 3-D and depth-perception capability with a binocular imaging scheme, allowing us to navigate and interact with objects in 3-D space.

Taking a page from nature's playbook, we are now adding human-like sensing and perception capabilities to computing and communications devices, to give them the abilities to "see," "hear," and "understand" human actions and instructions in natural and intuitive ways and use these new capabilities to interact with us.[6]

The industry is witnessing significant innovations and early commercial implementations of gesture-based interaction schemes based on real-time image capture and inference technologies. Until recently, most efforts were focused on 2-D computer vision and image-processing techniques for gesture-input recognition,[7] taking advantage of the 2-D image sensors that are now a ubiquitous part of computing and communications devices. However, implementations based on 2-D image sensors and processing are limited to simple gestures. Recent breakthroughs in

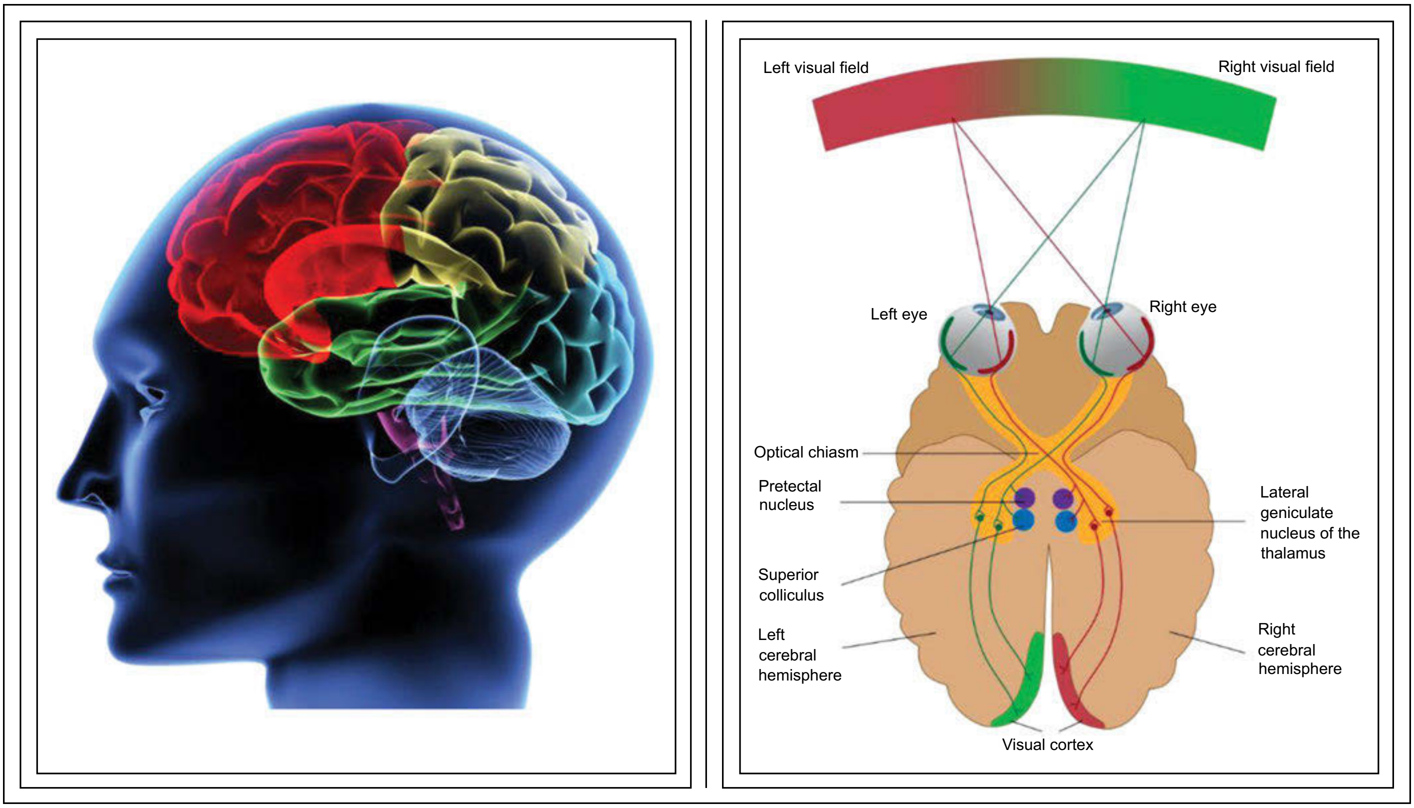

Fig. 2: At left, more than half of the human brain is dedicated to processing perceptual signals, enabling us to see, hear, understand, and interact with each other in natural ways. At right, the human-visual system perceives the world in 3-D with a binocular imaging scheme.

3-D imaging technologies are now enabling fine-grain rich user interactions and object manipulations in 3-D space in front of the display. There are various methods for capturing and interpreting real-time 3-D user inputs; three of the most prominent are (1) stereo-imaging-based computer vision, (2) projected structured-light-based 3-D imaging, and (3) time-of-flight techniques for depth-map determination.[8]

Stereo-imaging-based 3-D computer-vision techniques attempt to mimic the human-visual system, in which two calibrated imaging devices laterally displaced from each other capture synchronized images of the scene, and the depth for the image pixels is extracted from the binocular disparity. The technique is illustrated in Fig. 3 (left), where O and O′ are the two camera centers with focal length f, forming images of an object, X, at positions x and x' in their respective image planes. In this simple case, it can be shown that the distance of the object, perpendicular to the baseline connecting the two camera centers, is inversely proportional to the binocular disparity: $z = Bf/(x - x')$. Algorithms for determining binocular disparity and depth information from stereo images have been widely researched and further advances continue to be made.[9]

In the case of structured-light-based computer-vision methods, a patterned or "structured" beam of light, typically infrared, is projected onto the object or scene of interest; the image of the light pattern deformed due to the shape of the object or scene is then captured using an image sensor, and, finally, the depth map and 3-D geometric shape of the object or scene are determined using the distortion of the projected optical pattern. This is conceptually illustrated in Fig. 3 (middle).[10]

The time-of-flight method measures the depth map by illuminating an object or scene with a beam of pulsed infrared light and determining the time it takes for the light pulse to be detected on an imaging device after being reflected from the object or scene. The system typically comprises a full-field range imaging capability, including amplitude-modulated illumination source and an image sensor array with a high-speed shutter. Figure 3 (right) conceptually illustrates a method for converting the phase shifts of the reflected optical pulse into light intensity,[11] which allows determination of the depth map.

With real-time acquisition of 3-D data points using the techniques described above, rich human–computer interaction schemes can be implemented using recognition and inference techniques that enable interactions beyond touch screens. Besides these 3-D computer-vision technologies, there have also been significant interest and efforts in the research community in developing human–computer interfaces utilizing voice input, processing, and output.[12] Recent developments in this domain are starting to yield commercial success, with applications in mobile devices, consoles, and automotive markets. Furthermore, the combination of these sensing and perception domains makes it possible to implement multi-modal user interfaces.

As an example of such an implementation, we have recently developed and released the Intel Perceptual Computing Software Development Kit (SDK), which includes a small, light-weight, USB-powered 3-D imaging device with dual-array microphones, a set of libraries consisting of 3-D computer vision and speech processing algorithms, and Application Programming Interfaces (APIs) for application developers to utilize these libraries.[13] These tools allow developers to create immersive applications and interactive experiences that incorporate close-range hand and finger-level tracking, fine-grain gesture, and pose recognitions, speech recognition, facial analysis, 2-D/3-D object tracking, and augmented reality.

The 3-D imaging device included in the aforementioned SDK is specifically designed for close-range interactivity, including a 3-D depth sensor, a high-definition RGB sensor, and built-in dual-array microphones. Figure 4 shows some of the important capabilities and tools provided in the SDK, utilizing real-time computer vision and image-processing algorithms.

The image-capture module in the SDK provides an 8-bit RGB image and a 16-bit depth map, enabling the reconstruction of 3-D point clouds. The audio-capture module provides 1–2 channel PCM/IEEE-Float audio streams. The close-range finger-tracking module includes geometric node tracking and 7-point tracking of fingertips, palm center, and elbow. Advanced computer-vision algorithms provide an estimation of positions, volumes,

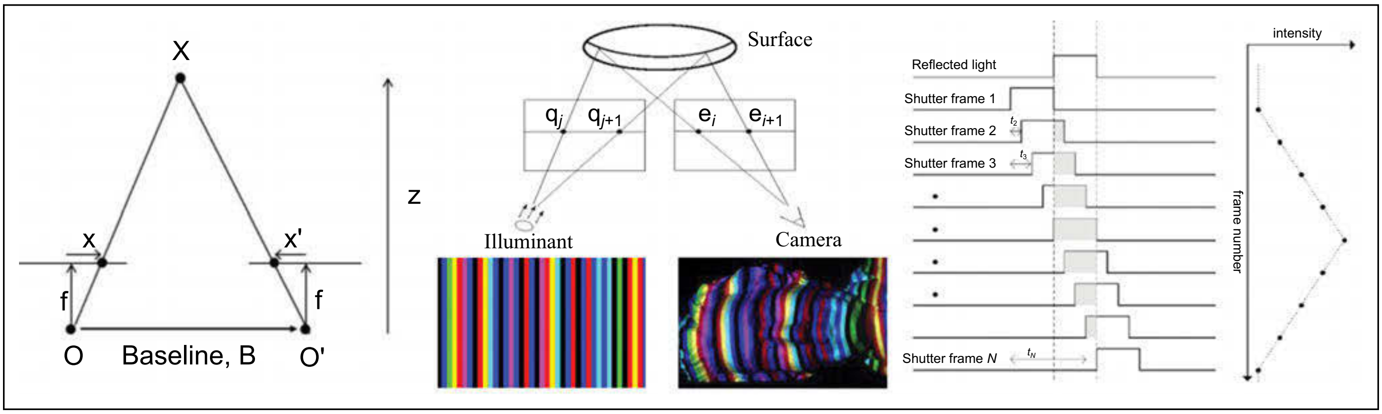

***Fig. 3:** Principles of 3-D image-capture technologies include, at left, stereo-3D imaging based on the geometric relationship between object distance and binocular disparity; in middle, a projected structured-light 3-D imaging method[10]; and, at right, a time-of-flight range-imaging technique using pulsed light reflection.[11]*

openness and handedness, recognition of a standardized set of poses such as thumb up/down and peace, gestures such as swipe left/right/up/down, circle and wave, and label maps for hand image and its parameters. The face tracking and analysis module includes landmark detection – eyes, nose, and mouth, facial attributes – age-group and gender detection, smile and blink detection, and face recognition. Other modules incorporate speech recognition and synthesis with voice command and control, short-sentence dictation, and text-to-speech synthesis; and 2-D/3-D object tracking with tracking of planer surfaces, reporting of position, orientation, and other parameters, and tracking of 3-D objects based on 3-D models.

Besides the libraries described above, we have also developed and released a computationally efficient articulated 3-D hand-skeletal tracking technique based on a physical-simulation approach using the 3-D imaging sensor.[14] This method fits a 3-D model of a hand into the depth image or 3-D point cloud generated by the 3-D imaging device, on a frame-by-frame basis, and imposes constraints based on physiology for accurate tracking of the hand and the individual fingers despite occasional occlusions. As shown in Fig. 5, this technology enables fine-grain versatile manipulation of objects in 3-D space.

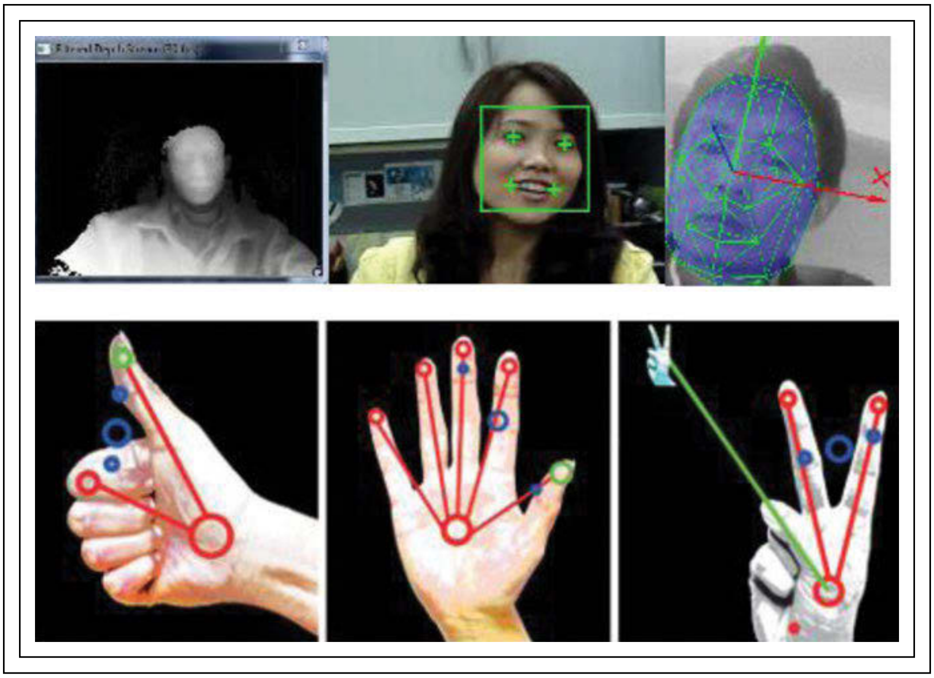

Fig. 4: At top left, a depth-image is captured using the 3-D-imaging device included in the Perceptual Computing SDK. The top middle figure shows color-image and face analysis and the top right figure shows 2-D/3-D tracking and augmented reality. The bottom row shows hand and finger-level recognition and tracking.

A New Class of Interactive Applications

Besides enhancing user interactions for some of the traditional applications, a new class of highly interactive applications and user experiences are made possible by multi-modal interaction schemes that combine multiple inputs such as touch, voice, face, and 3-D gesture recognitions in intuitive and engaging ways. Figure 6 shows two examples that are naturally enabled by 3-D gesture interactions in front of the display, rather than traditional 2-D inputs such as a mouse or touch screen. The image on the left shows a scenario in which the user is expected to reach out and "grab" a door knob, "turn" it, and "pull" it out of the plane of the display to "open" the door. The image on the right shows a "slingshot" application, in which the user "pulls" a sling with the fingers, directs it in the 3-D space, and "releases" it to hit and break the targeted elements of a 3-D structure.

These actions would be quite difficult to implement intuitively with a mouse, keyboard, or a touch screen. Implementations of 3-D gesture interactions using 3-D computer-vision algorithms result in more natural and intuitive user experiences for this type of application.

Besides gesture interactions and object manipulations in 3-D space, real-time 3-D imaging can also transform video conferencing, remote collaboration, and video blogging applications, as users can easily be subtracted

Fig. 5: An articulated model-based hand-skeletal tracking technology enables fine-grain versatile manipulation of objects in 3-D space. Source: Intel.

Fig. 6: Examples of interactive applications and experiences enabled by 3-D imaging technologies include manipulations of objects in the 3-D space in front of the display. Source: Intel.

from the background, or a custom background can be inserted using the depth map generated by the 3-D imaging device. Another category of applications that can be dramatically enhanced is augmented reality, where rendered graphical content is added to captured image sequences. Beyond the traditional augmented reality applications that currently use 2-D cameras, 3-D imaging can augment video content with 3-D models of objects and scenes and allow users to interact with elements in the augmented world.

Enabling Enhanced Interactions

Just as the introduction of the mouse and the graphical user interface three decades ago brought about numerous new applications on computers, and the proliferation of the touch interface enabled another set of new applications on smartphones and tablets over the past few years, 3-D user interfaces based on perceptual computing promise to usher in a new class of exciting and interactive applications on computing, communications, and entertainment devices.

This article has examined key natural user input technologies behind the emerging multimodal interaction paradigms that are paving the path to the era of perceptual computing and a new class of highly interactive applications and user experiences. Recent advances in 3-D computer vision with real-time 3-D image-capture techniques and inference algorithms, combined with improvements in speech recognition, promise to take human–computer interactions one step further into the 3-D space in front of the display.

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Tablet Display Technology Shoot-Out

Smartphones and tablets represent a new class of displays with requirements different from that of TVs and monitors. Here is where manufacturers are – and are not – meeting the challenges of ambient light and other considerations.

by Raymond M. Soneira

SMARTPHONES AND TABLETS represent a major product revolution for consumers, but these mobile devices have had an even greater impact on the display industry. Up until recently, most display technology was dedicated to producing large AC-powered TVs and computer monitors that are used almost exclusively indoors under controlled and often subdued ambient lighting. Laptops are the original mobile displays, but they have hefty batteries, often run on AC power, and are also typically used indoors under controlled and subdued ambient lighting.

Enter smartphones and their bigger cousins, the tablets, as the first truly mobile displays. They are essentially handheld screens operating primarily on battery power that are designed for the convenient viewing of content and images virtually anywhere. More importantly, they are often used under relatively high ambient lighting and with screens that are typically oriented anywhere from 45° to entirely horizontal (as when resting on a table). These angles typically catch and reflect substantially more light than the vertically oriented screens of TVs, monitors, and laptops. Because they are carried around everywhere, these devices are also much more vulnerable to breakage, so they almost always come with a hefty cover glass, which further complicates reflections from ambient lighting.

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In addition to being mobile computers that produce high-resolution text and graphics, these devices are also mobile HDTVs and photo viewers. They are expected to deliver excellent picture quality and color accuracy over a wide range of ambient lighting. Their onboard digital cameras and their frequent use for photo sharing among family and friends make picture quality and color accuracy much more important than for HDTVs because the viewers often know what the photo subject matter actually looks like, especially when the photos are viewed on a large tablet screen moments after being taken.

Last, but definitely not least, the displays are used at relatively close viewing distances, typically less than 15 in. Given their small screen sizes and high pixel resolutions, they require very high pixel densities, starting from around 125 up to the latest 450+ pixels per inch (ppi) displays. Compare this to a 50-in. 1920 × 1080 HDTV, which has just 44 ppi. In terms of the more physically relevant area density, pixels per square inch, that is up by a factor of 100:1 – very impressive!

The above represents an incredibly tough and comprehensive set of requirements for any display to deliver. While much has been accomplished in just a few years, there is still much more that needs to be done. In this article, I will use an extensive set of lab tests and measurements on a number of cutting-edge displays and display technologies to see how they are meeting these challenges. I will also suggest areas and paths for improvement in future mobile displays.

Tablet Displays and Display Technologies

The line between smartphones and tablets has become increasingly blurred, which has given rise to an intermediate category called phablets. For this article, I am classifying any mobile display with a 5.5 in. or greater screen diagonal as a tablet. I picked a representative set of high-end displays and display technologies in this size class, with the additional requirement that they had to be tested on a production class device (rather than as a standalone display or prototype). Four tablet displays were tested and analyzed in-depth, plus many others are mentioned where appropriate. Here they are:

OLED Displays and Technology

While most mobile displays are still LCD based, OLEDs have been capturing a rapidly increasing share of the mobile-display market. The technology is still very new, with the Google Nexus One smartphone, launched in January 2010, as the first OLED display product that received widespread notoriety. In a span of just a few years, this new display technology has improved at a very impressive rate, now challenging the performance of the best LCDs. Virtually all of the OLED displays used in current mobile devices are being produced by Samsung Display. Here, I test the Samsung Galaxy Note II, a 5.5-in. 1280 × 720 RGB OLED tablet, which is the largest OLED tablet display currently available. Samsung had previously offered a Galaxy Tab 7.7-in. RGB OLED tablet – so larger screens are likely again in the near future. On the high-

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resolution side, the recently released Galaxy S4 smartphone has a 1920 × 1080 5-in. 441-ppi PenTile OLED display, which will undoubtedly be extrapolated into the next generation of OLED tablets.

LCDs and Technology

LCDs encompass a very broad range of display technologies. While some tablets have launched with lower-performance twisted-nematic (TN) LCDs, most successful tablets now use higher-performance LCDs, often with in plane switching (IPS), fringe field switching (FFS), or plane-to-line switching (PLS).

400+ ppi LCDs: Apple started a major revolution in display marketing by introducing its "Retina Display" in 2010, having 326 ppi on the iPhone 4. While the display is not actually equivalent to the resolution of the human retina, people with 20/20 vision cannot resolve the individual pixels when the Retina Display is held at normal viewing distances of 10.5 in. or more. The introduction of the Retina Display made it clear that displays were no longer commodities but rather an important sales and marketing feature for mobile devices. The iPhone 4 also started a ppi and megapixel war similar to what happened with smartphone digital cameras, which are still experiencing an ongoing wild goose chase heading into the stratosphere. Hopefully, the same sort of competition will not occur with mobile displays.

The real question is how high do we need to go before reaching a practical visual ppi limit? That is a topic that I will analyze in detail in a future article. However, a new generation of 400+ ppi displays is already here, driven by the desire of many manufacturers to produce a full-HD 1920 × 1080 display in a phablet screen size. In 2012, HTC introduced its Butterfly/Droid DNA smartphone with a 1920 × 1080 5.0-in. 440-ppi display manufactured by Sharp that uses continuous grain silicon (CGS) rather than amorphous silicon (a-Si), which becomes increasingly inefficient at high pixel densities. Similarly, LG introduced its Optimus G Pro phablet with a 1920 × 1080 5.5-in. 403-ppi display that uses low-temperature polysilicon (LTPS), which I test here.

7-in. LCDs: The now very popular 7-in. tablet format was pioneered by the Barnes & Noble Nook Color, Amazon Kindle Fire, and Google Nexus 7. The latter two tablets had 1280 × 800 displays in 2012. After dismissing the smaller 7-in. tablets, Apple subsequently introduced its own iPad mini, with a 7.9-in. 1024 × 768 display with a (surprisingly) lower performance and a much smaller color gamut and higher reflectance than both the Nexus 7 and Kindle Fire. The Google Nexus 7 was tested as a representative of the 7-in. tablets.

10-in. High-Resolution LCDs: Apple started the tablet revolution in 2010 with the iPad, a 9.7-in. 1024 × 768 132-ppi display. It had a high-quality IPS/FFS display. Following the revolutionary iPhone 4's 326-ppi Retina Display, Apple introduced a third-generation iPad in 2012 with a 2048 × 1536 264-ppi Retina Display. There have been lots of competing 10-in. tablets, first typically with 1280 × 800 displays and then later with 1920 × 1080 and above displays. The Google Nexus 10 is the iPad's current closest display competitor with a 10.1-in. 2560 × 1600 IPS/FFS display. For the large 10-in. high-resolution tablets, I will test the Apple Retina Display iPad.

Reflective Displays and Technology

A number of reflective tablet display technologies have been under long-term development, including E Ink's electrophoretic displays, Qualcomm's mirasol, Amazon's Liquavista, and Pixel Qi. The only one to reach a significant production stage so far has been E Ink, including its 6–10-in. Pearl monochrome and Triton color displays. Here, I will test E Ink's 8-in. 800 × 600 Triton II color tablet in the High Ambient Light section below.

Display Properties and Display Marketing

The tablets are compared in Table 1, which lists their product specifications and display properties. While this article provides objective technical data and analysis of the displays, it is important to understand that all of these products are configured by marketing requirements designed to get the attention of consumers by appealing to their interests, preferences, and biases, and in some cases to their lack of technical knowledge.

Color Gamut

The color gamut is the range of colors that a display can produce. In some cases, color management is used to adjust the display's native color gamut in order to better match an industry-standard gamut. I am bewildered that the display industry is still widely using as a reference the NTSC color gamut, which was defined in 1953 and has been obsolete for over 30 years. This confusion spills over from display manufacturers, to device manufacturers, to journalists and consumers, who frequently quote and evaluate the color gamut in terms of the totally irrelevant NTSC gamut.

Table 1: Four tablets representing different display technologies are compared in terms of their product specifications and display properties.

Categories	Samsung Galaxy Note II	LG Optimus G Pro	Google Nexus 7	Apple iPad Retina Display
Display Technology	OLED RGB Stripe	LCD IPS LTPS	LCD FFS aSi	LCD IPS/ FFS aSi
Display Manufacturer	Samsung Display	LG Display	Hydis	Multiple
Screen Diagonal (in.)	5.5	5.5	7.0	9.7
Screen Area (sq. in.)	12.9	12.9	22.0	45.2
Screen Aspect Ratio	16:9 = 1.78	16:9 = 1.78	16:10 = 1.60	4:3 = 1.33
Display Resolution	1280 × 720	1920 × 1080	1280 × 800	2048 × 1536
Pixels per Inch (ppi)	267	403	216	264
20/20 Vision Viewing Distance where Pixels are Not Resolved (in.)	12.9	8.5	15.9	13.0

What is the relevant color gamut? Essentially, all current consumer image content is created using the sRGB and ITU-R BT.709 (Rec.709) standards. This encompasses digital cameras, HDTVs, the Internet, and computer content, including virtually all photos and videos. Note that standard consumer content does not include colors outside of the standard sRGB/Rec.709 gamut, so a display with a wider color gamut cannot show colors that are not in the original and only produce inaccurate exaggerated on-screen colors. The color accuracy of the images produced by a tablet will depend on how closely the display reproduces the colors of the sRGB/Rec.709 color space in both hue and saturation.

Table 2 lists and Fig. 1 shows the measured color gamuts for the tested displays together with the sRGB/Rec.709 standard. Note that they are plotted on a CIE 1976 uniform chromaticity diagram [rather than the non-uniform 1931 CIE diagram that is still (surprisingly) being used]. The color gamuts were measured in a perfectly dark lab. In a later section, I

Table 2: Four tablets representing different display technologies are compared in terms of lab measurements in absolute darkness at 0 lux

Categories	Samsung Galaxy Note II	LG Optimus G Pro	Google Nexus 7	Apple iPad Retina Display
Brightness and Contrast				
Maximum Luminance (cd/m^2) Full Screen Peak White	225 (Standard) 216 (Movie)	440	374	421
Peak Luminance (cd/m^2) Small-Window Peak White	289 (Standard) 273 (Movie)	440	374	421
True Black Luminance at Maximum Brightness (cd/m^2)	0	0.43	0.38	0.48
Dynamic Black Luminance at Maximum Brightness (cd/m^2)	0	0.31	0.32	0.48
Contrast Ratio at 0 lux Relevant for Low Ambient Light	Infinite	1027 True 1419 Dynamic	984 True 1169 Dynamic	877 True
Colorimetry and Intensity Scales				
Color Gamut (%) Relative to sRGB / Rec.709	134 (Standard) 106 (Movie)	98	87	99
White Point (K) Correlated Color Temperature	7675 (Standard) 6597 (Movie)	8427	6714	7085
Intensity Scale Gamma	2.58	2.28–2.56	1.95–2.14	2.20
Screen Reflectance				
Average Screen Reflectance (%) Light From All Directions	4.9	7.7	5.9	7.7
Specular Mirror Reflectance (%) Percentage of Light Reflected	6.4	10.1	7.2	9.9
Contrast Rating for High Ambient Light	46–59 (Standard) 44–56 (Movie)	57	63	55
Variation with Vertical Viewing Angle				
White Luminance at 30° Compared to 0° (%)	78	41	44	43
True Black at 30° at Maximum Brightness (cd/m^2)	0	0.31	0.24	0.35
Dynamic Black at 30° at Maximum Brightness (cd/m^2)	0	0.22	0.20	0.35
Contrast Ratio at 30° Relevant for Low Ambient Light	Infinite	582 True 820 Dynamic	686 True 823 Dynamic	526 True

will examine how the color gamut changes with the ambient light level.

LCDs have had a difficult time reproducing the full sRGB/Rec.709 color gamut as a result of spectral light efficiency issues that decrease the luminance and power efficiency of the display when the color saturation is increased. Most mobile LCDs (including the iPad mini and Microsoft Surface RT) until recently delivered only 55–65% of the sRGB/Rec.709 color gamut, but many newer tablets are producing 80–100% of the standard gamut, including the Google Nexus 7, LG Optimus G Pro, and Apple Retina Display iPad tested here, the latter two with close to a perfect 100% gamut (in the dark). Quantum dots, which can efficiently increase the display color gamut, are beginning to appear on LCDs from smartphones up to HDTVs. A large color gamut also provides an important advantage when displays are viewed in high ambient lighting, which I will discuss below.

OLEDs currently have the opposite problem of traditional LCDs, too large a native color gamut, which requires color management in order to deliver accurate sRGB/Rec.709 colors. The resulting color mixtures require more display power and processing power to produce. The Samsung Galaxy Note II has four display modes with different color gamuts and white points – here I test the Standard and Movie modes; the latter provides a closer match to sRGB/Rec.709.

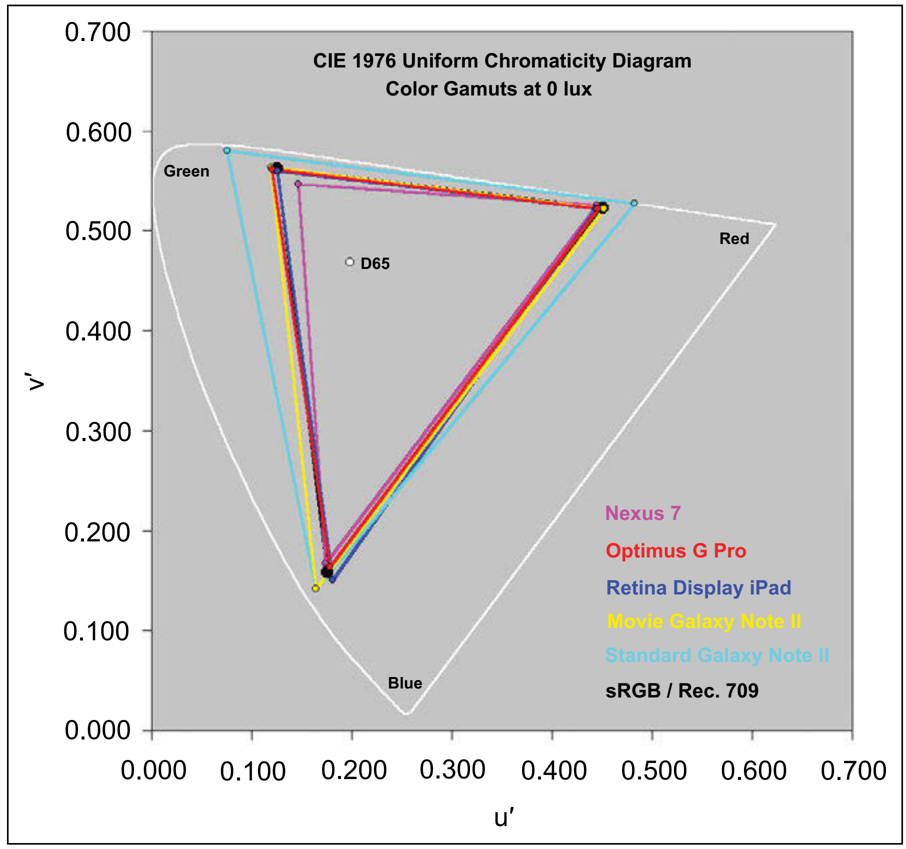


Fig. 1: The color gamuts of the displays in absolute darkness 0 lux were measured using a spectroradiometer and plotted on a CIE 1976 Uniform Chromaticity Diagram. The outermost white curve represents the limit of human color vision. A given display can only reproduce the colors that lie inside of the triangle formed by its primary colors. The black circles identify the sRGB/Rec.709 Standard Color Gamut. Note that the black lines connecting the black circles are obscured by the individual display gamuts. The Galaxy Note II was measured both in its native Standard Mode and a color managed Movie Mode. D65 is the standard white point.

Luminance and Intensity Scales

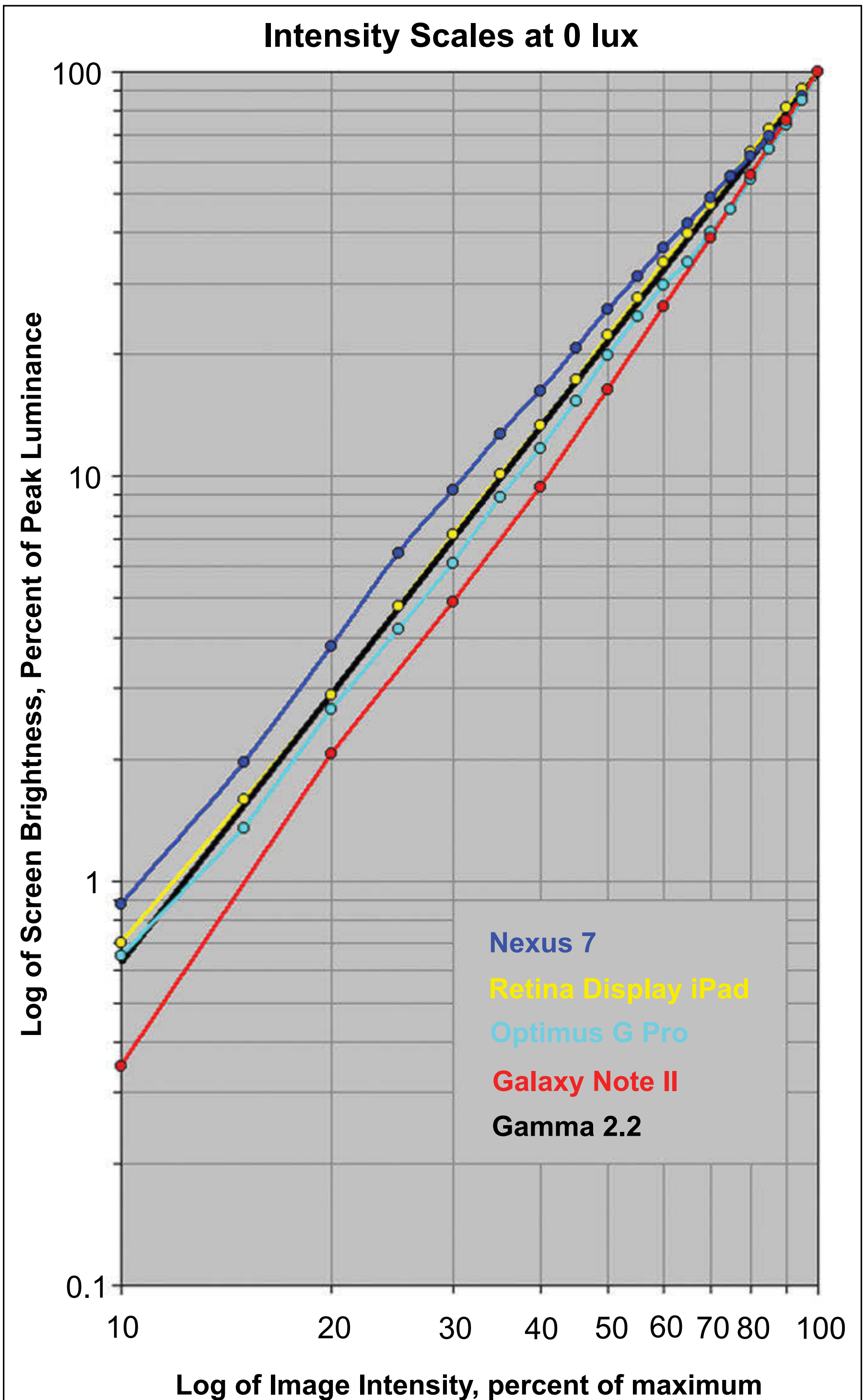
The intensity scale (sometimes called the gray scale) not only controls the image contrast within all displayed images, but also how the red, green, and blue primary colors mix to produce all of the on-screen colors. The steeper the intensity scale, the greater the image contrast and the higher the saturation for displayed color mixtures. So, if the intensity scale does not follow the standard then the colors and intensities will be wrong everywhere.

The intensity scales for many standards, including sRGB/Rec.709, follow a power law with a gamma exponent of 2.2. While many displays get sloppy or creative with their intensity scales, maintaining a power law (a straight line on a log–log graph) is extremely important because that preserves the red, green, and blue luminance ratios, and therefore the hues and saturation values for color mixtures regardless of signal level. Gamma values higher than 2.2 can be used to increase image contrast and color saturation, which is helpful when the color gamut is too small.

Table 2 includes measurements of the peak white luminance, white-point correlated color temperature, black luminance, and contrast ratio (in the dark). Some displays make some of these values variable (often called dynamic) in order to reduce power consumption or for an exaggerated visual effect. For LCDs, a dynamic black is implemented by dimming the backlight for low average picture levels (APLs). For OLEDs, the luminance is typically reduced for high APLs. LCDs are currently significantly brighter and OLEDs have perfect blacks. However, because the LCDs have contrast ratios of around 1000:1, their black luminance decreases proportionally with the screen brightness setting, so their non-perfect blacks will be satisfactory for most content under most ambient-light viewing conditions. Nonetheless, the OLED perfect blacks appear stunning for applications with significant black or dark content at low ambient light levels. In a later section, I will discuss what happens at higher ambient light levels.

Figure 2 shows the intensity scales, which were measured in a perfectly dark lab. The Retina Display iPad has a virtually perfect intensity scale. The Galaxy Note II (both Standard and Movie modes) has a fairly straight but much too steep intensity scale, while the Optimus G Pro and Nexus 7 have somewhat irregular intensity scales. In a later section, I will examine how the intensity scales change with the ambient light level.

Tablets (and smartphones) generally only provide one user adjustable parameter for the display – a brightness control. But differing user preferences and various applications would significantly benefit from providing additional display color and image contrast controls that would allow the user to better customize the display. One interesting technical development is that OLED displays use digital pulse width modulation to produce their intensity scales and the red, green, and blue luminance levels. This makes it possible for them to precisely vary and digitally control the intensity scales, gamma values, white points, color calibration, and management of the display in firmware or software. Many OLEDs, including the Samsung Galaxy Note II tested here, have started to take advantage of this functionality by providing several display modes with different color gamuts and white points. I hope to see this extended in future OLED products. LCDs, on the other hand, are non-linear analog devices, so accurately varying or changing their many calibration parameters is more difficult. It can be done, but requires different hardware configurations and additional factory calibration. However, the functional benefits together with its marketing features and advantages make this worthwhile.



Viewing-Angle Performance

While tablets are used mostly as single-viewer devices, the variation in display performance with viewing angle is still very important because single viewers frequently hold a display at a variety of vertical viewing angles. When the display is lying on a table, the vertical viewing angle is typically 45° or more.

For LCDs, the typical 176+° advertised viewing-angle specification is misleading because it is defined for the angle where the (0-lux absolute darkness) contrast ratio falls to a miniscule 10, which is typically 1% of the contrast ratio for viewing at 0°. This highly exaggerated specification also makes it close to impossible for any new display technology (including LCD) that offers better viewing-angle performance to convey this to prospective investors, customers, and consumers.

Fig. 2: *The measured intensity scales of the displays in absolute darkness 0 lux are plotted as the log of screen brightness versus the log of the signal image intensity. The standard power-law gamma of 2.2 is the straight black line. The Retina Display iPad has a virtually perfect intensity scale; the other displays are either somewhat too steep or too shallow, which affects the image contrast in addition to the hue and saturation of color mixtures.*

Table 2 lists the variation in peak luminance, black luminance, and contrast ratio for a modest 30° vertical viewing angle. Note that the horizontal viewing-angle performance for multiple side-by-side viewers or for viewing at azimuth angles other than purely horizontal or vertical are often different. LCDs typically show a large 55% decrease in peak luminance at 30°. However, IPS/FFS LCDs show no visible color shifts with viewing angle, typically less than 2 JNCD (Just Noticeable Color Difference) at 30°. On the other hand, OLEDs show a much smaller 20% decrease in luminance, but a somewhat larger (but not objectionable) color shift that is due to anti-reflection and other optical elements.

Screen Reflectance

Virtually all smartphone and tablet screens can function as mirrors good enough to use for personal grooming – but that is a really bad feature, especially for tablets because their larger screens can not only reflect the viewer's face but also a wide range of objects that are behind the viewer. The reflections become obvious if you observe the tablet with the display turned off. When the display is on, those reflections are still there and wash out the image contrast and colors. In bright ambient lighting, the screen may be impossible to read without the user reorienting himself or the tablet. An additional problem with mirror (specular) reflections is that the eye automatically and involuntarily tries to focus on the more distant reflected objects instead of the screen, which is much closer. That continual refocusing can cause eye strain and fatigue.

While some HDTVs, computer monitors, and laptops have an anti-glare matte or haze finish that diffuses specular reflections, virtually all tablets and smartphones have a glossy mirror finish. One reason could be the manufacturing cost, another could be just to continue with traditional glossy cover glass designs, but it might also be that some consumers may shy away from the appearance of the hazy matte finish on such screens. In general, the matte and haze finishes improve overall screen visibility most of the time, but they will sometimes reflect ambient light that would not be seen with a specular mirror surface. I will explore this issue in detail in a future article. I hope that we will soon see more tablets and smartphones with an anti-glare cover glass rather than relying on after-market products that do not perform as well.

Lowering the screen reflectance is extremely important because reducing it by, for example, 10% allows the display to run with 10% less luminance and power at high ambient lighting, while still providing equivalent screen visibility. While lowering the reflectance comes with an additional manufacturing cost, it can produce a significant improvement in screen visibility and battery running time.

Table 2 includes both the specular and average reflectance for the tablets. The specular value was measured by bouncing a narrow highly collimated beam of light off the screen and the average reflectance was measured by placing each tablet inside a large integrating hemisphere and taking measurements through a small opening near the top. The best mobile displays now show average reflectance values of 4.5%, which is a substantial improvement over the 20+% values I measured in 2006. The higher reflectance values for the LG Optimus G Pro and Apple iPad Retina Display result from an air gap between the cover glass and the display. A version of the LG Optimus without the air gap arrived too late to be included in these tests.

Display Performance in Ambient Light

Displays are almost always lab tested in the dark, but they are never used in the dark. In fact, tablets are often used in very bright ambient lighting, which can significantly degrade their image and picture quality. All of the earlier lab measurements were made in the dark, so in this section I repeat the measurements for a number of different ambient light levels to see how the performance changes (degrades).

Table 3: Four tablets representing different display technologies are compared in terms of lab measurements in ambient light

Categories	Samsung Galaxy Note II (Standard Mode)	LG Optimus G Pro	Google Nexus 7	Apple iPad Retina Display
Contrast Rating for High Ambient Light	59	57	63	55
White Level Luminance (cd/m^2) Small-Window Peak White	291 (at 125 lux) 297 (at 500 lux) 320 (at 2000 lux)	443 (at 125 lux) 452 (at 500 lux) 489 (at 2000 lux)	376 (at 125 lux) 383 (at 500 lux) 411 (at 2000 lux)	424 (at 125 lux) 434 (at 500 lux) 472 (at 2000 lux)
Black Level Luminance at Maximum Brightness (cd/m^2) True Black – Not Dynamic	1.9 (at 125 lux) 7.7 (at 500 lux) 30.9 (at 2000 lux)	3.4 (at 125 lux) 12.7 (at 500 lux) 49.2 (at 2000 lux)	2.7 (at 125 lux) 9.6 (at 500 lux) 37.1 (at 2000 lux)	3.7 (at 125 lux) 13.1 (at 500 lux) 51.2 (at 2000 lux)
True Contrast Ratio	153 (at 125 lux) 39 (at 500 lux) 10 (at 2000 lux)	130 (at 125 lux) 36 (at 500 lux) 10 (at 2000 lux)	139 (at 125 lux) 40 (at 500 lux) 11 (at 2000 lux)	115 (at 125 lux) 33 (at 500 lux) 9 (at 2000 lux)
Color Gamut (%) Relative to sRGB / Rec. 709	112 (at 500 lux) 93 (at 1000 lux) 69 (at 2000 lux)	77 (at 500 lux) 61 (at 1000 lux) 42 (at 2000 lux)	67 (at 500 lux) 54 (at 1000 lux) 38 (at 2000 lux)	76 (at 500 lux) 61 (at 1000 lux) 41 (at 2000 lux)

The popular and often quoted contrast ratio is valid only in the dark and relevant only at very low ambient light levels. For higher ambient light levels, I have defined a "Contrast Rating for High Ambient Light" listed in Table 2, which is the ratio of peak white luminance divided by the average screen reflectance in percent. It is effectively a signal-to-noise ratio that provides a visual figure of merit for displays in high ambient light. This simple metric accurately evaluates high-ambient-light display performance and also demonstrates how luminance and reflectance offset each other. Note that smartphones currently perform much better than tablets on this.

To make the high-ambient light measurements, I placed the tablets inside a large integrating hemisphere with a bright light source that produces a uniform isotropic light distribution. A small opening near the top of the hemisphere is used to make the spectroradiometer measurements and screen shots. I can set the illuminance to any value between 0 and 60,000 lux, which is half the value of direct sunlight at noon during the summer months at middle latitudes. I repeated various measurements at 125 lux, which corresponds to dim residential lighting, 500 lux, which corresponds to typical office lighting, 1000 lux, which corresponds to very bright indoor lighting or outdoor lighting with an overcast sky, and 2000 lux, which corresponds to typical outdoor daylight in heavy shade. The screen shots were also done at 20,000 lux, which corresponds to full daylight not in direct sunlight.

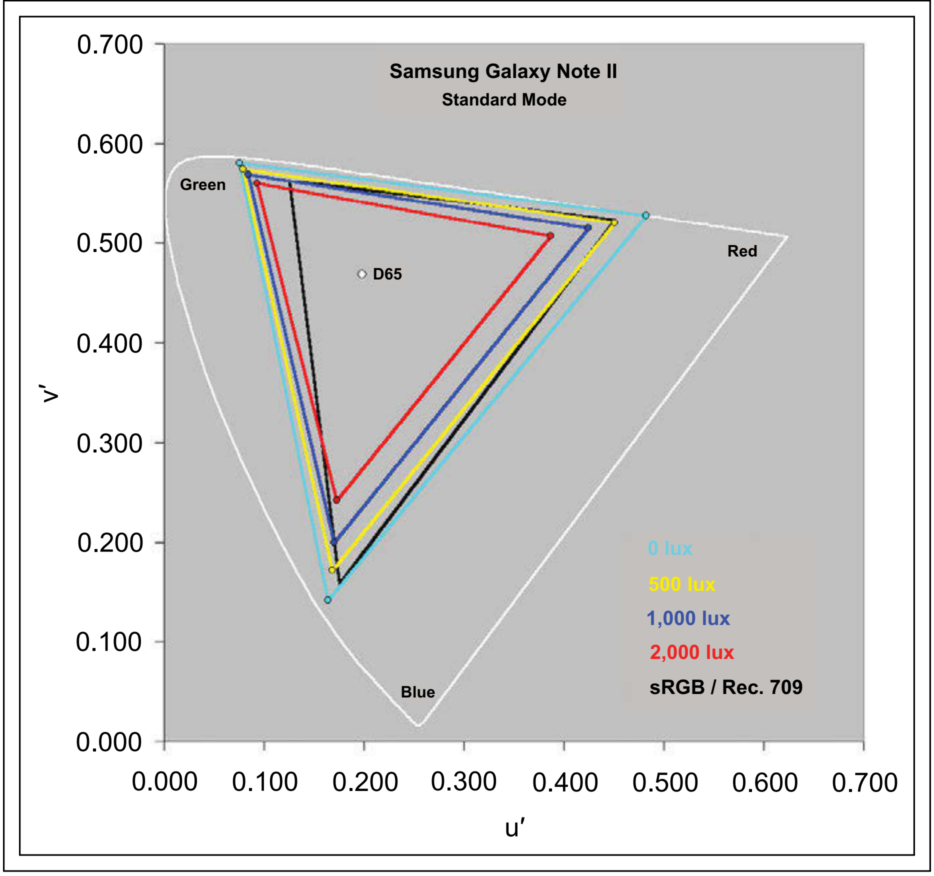


Fig. 3: The measured color gamut of the Samsung Galaxy Note II Standard Mode is shown at various ambient light levels from 0 lux (absolute darkness), 500 lux (typical office lighting), 1000 lux (very bright indoor lighting or outdoor lighting with an overcast sky), and up to 2000 lux (outdoor daylight in heavy shade) plotted on a CIE 1976 Uniform Chromaticity Diagram as in Fig. 1. Note that the color gamut progressively shrinks as the ambient light level increases. This increasingly washes out the image colors.

Table 3 lists the measured luminance, contrast ratio, and color gamut for the tested tablets at the indicated lux levels. Their relative performance closely follows the Contrast Rating for High Ambient Light for the tested tablets, which all (coincidentally for these tablets) have very similar values. Note that the black-level luminance is dominated by reflected ambient light even at 125 lux (but the Galaxy Note II is notably better due to a combination of low reflectance and zero native black luminance). The true contrast ratios fall from roughly 1000 or more at 0 lux, to 150 at 125 lux, to just 10 at 2000 lux.

Display Measurements in Ambient Light

Figure 3 shows the variation in color gamut with ambient light just for the Samsung Galaxy Note II. Since the color gamut decreases monotonically with increasing ambient light, there is a significant advantage to having a native gamut that is much larger than the standard gamut. This is possible for OLEDs and LCDs with quantum dots. At low ambient light levels, color management can be used to progressively reduce the gamut in order to match the standard. With color management connected to an ambient-light sensor, the display would be able to maintain an accurate visual color gamut over a wide range of ambient lighting. We will discuss this further below.

Figure 4 shows the variation in intensity scale with ambient light just for the Apple Retina Display iPad. The intensity scales flatten progressively as the ambient lighting level increases, which reduces image contrast. In order to compensate for the effect of reflected ambient light and improve the perceived visual image contrast, the display's native intensity scale should be dynamically steepened based on the ambient light level measured by the ambient-light sensor so that the composite intensity scale with reflected light still matches the standard intensity scale as far as possible. This will also improve color saturation.

Figure 5 shows screen shots of the displays with a DisplayMate Color Scales test pattern at 0, 2000, and 20,000 lux – the latter corresponds to full outdoor daylight that is not in direct sunlight. At 20,000 lux, the contrast ratios for all four tablets have decreased to roughly 2:1. I have also included the E Ink reflective electrophoretic tablet display mentioned earlier, which maintains color and image contrast independent of ambient light.

While at low ambient light levels, its color saturation and image contrast are less than the other displays; at high ambient light levels, its steady performance eventually matches and then overtakes the other displays.

These are the major trends to follow in the Fig. 5 screen shots as the ambient light levels increase:

- The borders between the photos are at true black. Use them to compare the black levels in the photos. Note the progressive increase in the brightness of what is supposed to be a black background. The tablets with lower average reflectance in Table 2 have the darker backgrounds. The different color tints of the backgrounds indicate differences in the spectra of the light that is being reflected.
- Note the progressive fading and disappearance of the dimmer intensity steps. Because of the differing camera exposure levels, what matters is the number of color and gray steps that can be seen in each photo. The gray scales generally fade differently from the color scales.
- Note the progressive loss of color saturation for the different intensity steps. The tablets with higher color saturation have greater visibility at high ambient light levels.
- The reflective E Ink tablet shows the greatest number of gray-scale steps, and its color saturation is fairly constant with the ambient light level.

Ambient-Light Sensors and Automatic Brightness

Automatic brightness is implemented with an ambient light sensor. Unfortunately, all of the implementations that I have tested are close to functionally useless (and many other reviewers agree), so users frequently turn them off and go back to fixed high manual brightness. It appears that automatic brightness is still primarily a marketing feature that has not yet

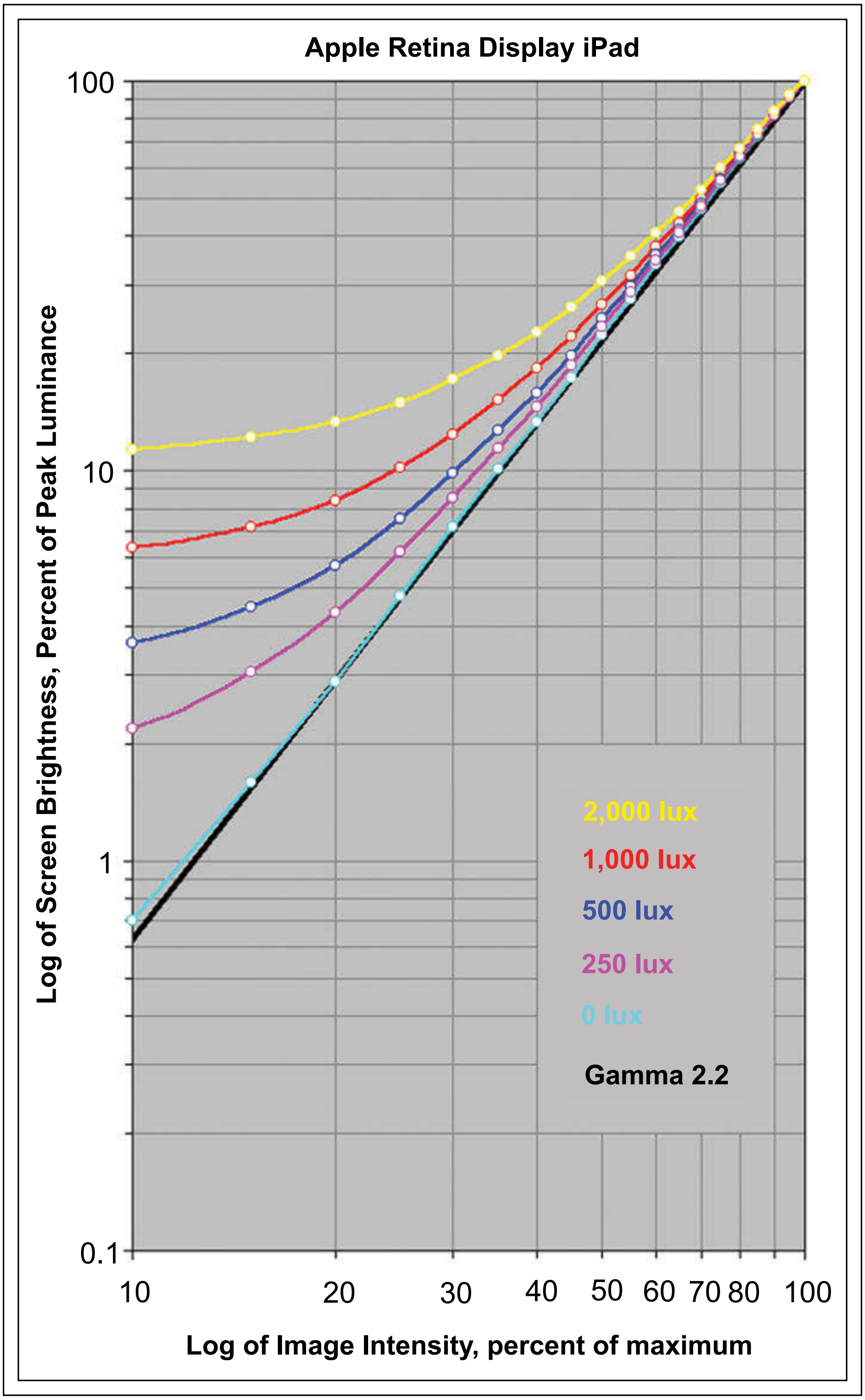


__Fig. 4:__ The measured intensity scale for the Apple Retina Display iPad is shown at various ambient light levels from 0 lux (absolute darkness), 250 lux (typical residential lighting), 500 lux (typical office lighting), 1000 lux (very bright indoor lighting or outdoor lighting with an overcast sky), and up to 2000 lux (outdoor daylight in heavy shade) plotted as the log of screen brightness versus the log of the signal image intensity as in Fig. 2. The standard power-law Gamma of 2.2 is the straight black line. Note that the intensity scale progressively flattens as the ambient light level increases. This increasingly washes out the image contrast.

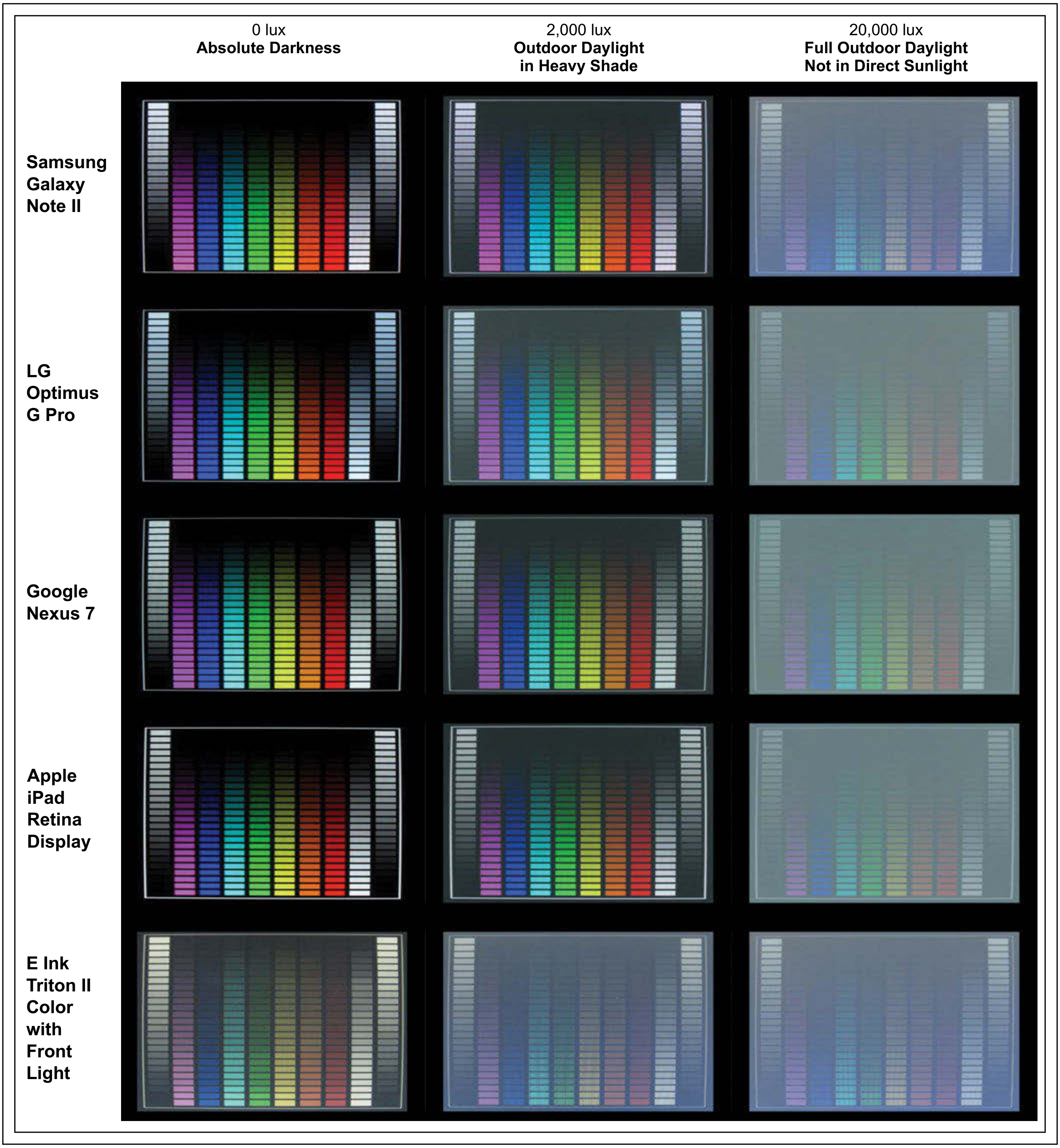


Fig. 5: Shown are tablet screen shots in high ambient light. Because of the wide range of ambient light levels and screen reflectance values, the screen shots were taken with a camera set for automatic exposure. As a result, the exposure levels vary between the tablets, but that is also the same way that our eyes would process each image. All of the photos were taken at the display's maximum brightness setting.

received sufficient engineering support and actual lab testing – in most cases the automatic brightness calibration values appear to have been set semi-arbitrarily by a software programmer.

What else is wrong? The ambient-light sensor is generally installed with a narrow acceptance angle and is typically placed near the top center of the display bezel, so it winds up measuring the brightness of the viewer's face instead of the actual ambient light levels that determine the reflected glare and the surrounding light that determines the eye's adaptation level (pupil size). So, more than one sensor is needed. When the brightness changes, the very different time scales and slew rates for increasing and decreasing the screen brightness need to be set appropriately. Furthermore, most Android devices just have a simple check box for automatic brightness, with no way for the user to adjust the brightness based on visual preferences and application. Figure 6 proposes how to properly implement automatic brightness with a user control.

Suggestions for the Next Generation of Tablet Displays

All of these tablets perform better than most HDTVs, computer monitors, and laptop displays from just a few years ago. While a lot has been accomplished, there is still much more that needs to be done. Below, I suggest areas and paths for improvement in the next generation of tablet displays. These suggestions also apply to smartphones, HDTVs, computer monitors, laptops, public signage displays, automobile displays, and just about all existing displays that are used in regular ambient lighting.

Higher Power Efficiency and Pixel Densities: Most current displays use a-Si backplanes, which become increasingly inefficient at high pixel densities. Existing higher-performance LTPS and CGS backplanes are considerably more expensive. The upcoming IGZO technology offers better performance at an intermediate cost. More advanced metal oxides appear to hold an important key to higher-performance and high-pixel-density displays at a lower manufacturing cost.

Lower Screen Reflectance: The best mobile displays currently have an average reflectance of 4.5%. Just lowering the reflectance down to 4.0% is equivalent to a 12.5% increase in luminance (or an 11% decrease in display power) and would also noticeably improve high-ambient-light screen performance. This can be accomplished by eliminating separate touch layers and by using improved anti-reflection optics and coatings.

Versatile and Accurate Color Management and Calibration: Displays that are factory calibrated to produce photos and images with accurate image contrast and color are rare and remain a wish list item that could become a great marketing feature. Users should be allowed to adjust the white point, image contrast, and color saturation of a display according to their personal preferences and application.

Improved Display Performance with Ambient Light: The display system needs to be significantly improved in order to properly and efficiently operate under a wide range of ambient lighting – a major weakness with all existing tablets and smartphones. They need improved ambient-light sensor implementations, properly calibrated automatic brightness together with a user adjustment control, dynamic intensity scales and color management based on the ambient light level, and very different slew rates and time scales for increasing and decreasing the screen brightness.

Most important of all, right now the user interface for all automatic brightness controls is completely backwards – the light sensor

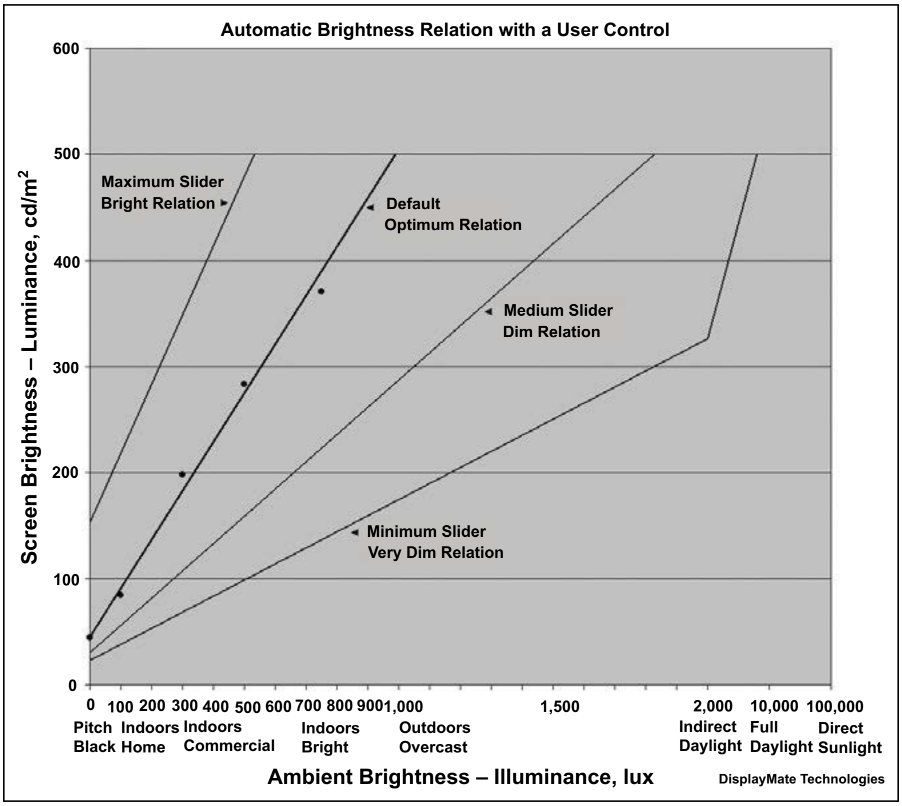


Fig. 6: The test's optimum visual screen brightness settings for different ambient light levels were determined by reading a New York Times *Web page on an iPhone for optimum visual comfort and readability (not too bright or too dim). The luminance and illuminance levels were measured. They are the black data points with their trend line, which is the proposed default brightness versus illuminance relationship. The other lines show a wide range of alternative brightness relationships from aggressively bright to aggressively dim with an ambient light level that should be coupled with an automatic brightness slider to allow the user to choose the relationship they want with ambient light. The graph is linear from 0 to 2000 lux and then jumps in steps to 10,000 and 100,000 lux. The labels from pitch black to direct sunlight roughly identify the lux levels associated with them.*

measures the ambient light and the tablet (or smartphone) sets the screen brightness based on some fixed and poorly designed algorithms. The solution is very simple – do it in the opposite way – the user initially adjusts the screen brightness manually to whatever she wants for the current ambient lighting. The ambient light sensor then measures this light level. The value is recorded and then used to interpolate the screen brightness whenever the ambient lighting changes.

The Next Generation of Mobile Displays

The major necessary developments for upcoming generations of mobile displays will come from improvements in image and picture quality in real-world ambient-light viewing conditions. The key will be improved sensors and algorithms that dynamically change the display's brightness, intensity scale, white point, color gamut, and overall calibration in order to automatically correct or compensate for reflected glare and image washout from ambient light. A significant bonus is that the display can then be used at lower brightness and power settings, which will increase the battery running time. These same issues apply to just about all displays. The companies that succeed in implementing this new strategy will take the lead in the real-world use of display technology.

Acknowledgment

Much of the information in this article is drawn from my extensive *Display Technology Shoot-Out* article series covering tablets and smartphones (and related articles on HDTV and multimedia displays). They are now all available on the www.displaymate.com website. For additional information on any of the topics covered here, refer to the Mobile Display and HDTV Display categories under Display Information for the list of relevant articles provided. ■

Tablets and Other Handheld Display Devices for Medical Imaging: An Image-Quality Perspective

A research team predicts that the next generation of handheld displays might enable on-demand viewing of medical diagnostic images – available anywhere, anytime.

by Aldo Badano, Asumi Yamazaki, Peter Liu, and Wei-Chung Cheng

THE use of handheld viewing devices in medical-imaging applications has seen a tremendous increase in the last couple of years. Applications of current interest range from using the handheld as an aid in the acquisition of patient images in remote locations[1] to the primary and secondary physician consultation of medical images from a variety of imaging modalities.[2] Imagine being able to view and refer to diagnostic images of yourself or a family member on a handheld device while consulting with your physician. Despite the limited diagnostic utility of such a scenario, prompt access to images from your electronic medical record might contribute to your understanding of treatment options and thus help you make more informed decisions about alternative procedures. You would also be able to use your handheld device to share medical images with specialists in order to request second opinions. Yet another advantage of being able to view medical images on handheld devices might be when physicians need to make decisions within a limited time frame and do not have immediate access to a medical-grade workstation for image interpretation.

These scenarios, although not quite a reality as of today, will soon become the norm. The display industry is working toward providing handheld display technology that is capable of offering all the relevant medical imaging data. At this point, interpretation of the data will no longer be hindered by limitations in device image quality.

Interest in the above applications has been fostered by the availability of high-quality handheld display devices with higher pixel density, lower noise, and wider color gamut. Amidst these improvements, however, current users are faced with display characteristics that differ substantially from dedicated medical workstation displays. Moreover, and of particular relevance to this article, these characteristics differ substantially among handheld devices. It is then of great importance to the medical-imaging community to understand the benefits and limitations of handheld devices for the viewing of diagnostic medical images from the perspective of image quality and its effect on the detectability of disease conditions and abnormalities in a patient's image data.

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Recent Studies

Studies of diagnostic accuracy for handheld devices typically compare the diagnostic performance of a set of human readers on workstations against their performance on handheld displays. A number of recent reports suggest that for some devices and some visual tasks associated primarily with less-demanding areas of medical imaging, diagnostic performance with handheld displays is comparable to the existing practice of reading images on workstations or dedicated medical displays. For instance, McNulty *et al.* investigated the diagnostic accuracy of a tablet computer (first-generation iPad) in comparison with a Digital Imaging and Communications in Medicine (DICOM) calibrated or secondary-class LCD in the case of interpreting computed tomography (CT) and magnetic resonance images in emergency exams[3] and suggested that tablets can be considered useful aids in the initial image interpretation stages when medical displays are not available. Another recent paper by Christopher *et al.* compared recommendations from ophthalmologists using a first-generation iPad with those made using a desktop display and found that the recommendations were similar.[4]

In a recent study by John *et al.*, tablet computers with larger screens, high pixel counts, and touch-screen interfaces were found to be advantageous compared to mobile-phone

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devices for viewing radiological images.[5] (The study also noted that tablets suffered from software instability and were of limited use for image manipulation such as zooming, panning, and annotating due to their small size.) McLaughlin *et al.* compared a tablet computer (first-generation iPad) with a diagnostic 2-Mpixel monochrome LCD and found no reporting discrepancies. Similar results were described by Johnson *et al.* on a similar experiment comparing radiologists' interpretative performance of computer tomography (CT) images on the tablet to interpretation on a conventional PACS display.[6] In addition, a similar recent study by Park *et al.* examined next-generation tablet computers (second-generation iPad) as teleradiology tools for evaluating brain CT7 and found that clinicians using tablets with a stable Internet connection could provide reliable remote evaluations.

As these previous studies demonstrate, experiments with human subjects and clinical evaluations seem to indicate that handheld medical image viewing can in some cases be as reliable as readings performed with dedicated medical monitors. However, many of these studies and their comparative findings are limited to specific device models and to specific viewing conditions that would not always be representative of actual ambient illumination conditions where these devices are utilized. Although the image-quality characteristics of medical workstation displays have been extensively documented (see, for instance, Ref. 8), handheld display devices have not yet been fully characterized in terms of spatial resolution, spatial noise, luminance response, and reflectance for various sizes and technologies, including LCDs and OLED displays using a consistent measurement methodology. Which of the many aspects of display device performance are more relevant for medical image viewing applications?

Image Quality: What Matters?

Among the display characteristics that need to be considered for evaluating image quality in a handheld display device, the ones with the most significant direct effect on performance are luminance response, spatial resolution, noise, and reflectance properties.

Luminance Response

The performance of a display device depends strongly on its ability to represent image values in a manner that is close to optimal and consistent for human reader interpretation of image data. Luminance performance is typically assessed using a photometric measurement device to compare the luminance output of the display device against the target model for image presentation, which in medical imaging is typically the expected contrast response given by the DICOM Grayscale Standard Display Function (GSDF) model based on a perceptually linear scale.

Table 1 shows the minimum and maximum luminance values and the luminance ratios because the handheld display brightness settings are fixed at maximum for a variety of devices. In general, we observe that OLED displays have higher luminance ratios due to the low minimum luminance values compared to that of LCD devices. It is worth noting that the medical monitors are calibrated to GSDF gray-scale mapping while the handhelds are calibrated to the original out-of-the-box settings. While the medical monitors comply with GSDF, all handheld devices exhibit a contrast response outside of the tolerance limit for secondary workstations given by Task Group 18 recommendations[9] even at the maximum brightness settings. (TG18 was a national task force consisting of medical-imaging experts focused on the performance evaluation of electronic-display devices.)

The results of the analysis could significantly vary under the manually selected or automatic brightness setting.

Reflectance

Because handhelds are used in varying viewing conditions with differing amounts of ambient illumination, display reflectance is one of the most important features of the device performance that affects image quality. The deleterious influence of ambient light reflections has been documented for workstation medical monitors and has been dealt with by using a correction to the GSDF presentation look-up-table (LUT) that compensates the luminance scale.[10] Reflectance is typically characterized by specular (R_s) and diffuse (R_d) components and measured under a hemispherical illumination geometry.[11] Figure 1 shows diffuse reflection coefficients R_d for all devices as a function of the specular reflection coefficients R_s.

All handheld displays exhibit higher R_s than workstation displays, while some of them have relatively similar diffuse reflectance coefficients compared to workstation displays.

The reflectance measurements suggest that some handhelds suffer more in terms of image quality in the presence of higher ambient illumination. For instance, when used in a viewing environment with 50 lux at the face of the display, medical workstation devices will

Table 1: Specifications for the display devices tested in this study appear with their corresponding measured minimum and maximum luminance values and luminance ratios. The unit for luminance is cd/m^2. *LR* is the ratio of maximum to minimum luminance.

Display	Screen size (in.)	Pixel array	Pixel pitch (mm)	L_{min}	L_{max}	LR
Phone1-LCD	3.5	320 × 480	0.156	4.44	703	158
Phone2-OLED	3.7	480 × 800	0.101	0.262	395	1510
Phone3-OLED	4.0	480 × 800	0.109	0.300	522	1740
Tablet1-LCD	9.7	768 × 1024	0.192	0.953	495	520
Tablet2-LCD	10.1	800 × 1200	0.170	1.31	680	519
Tablet3-LCD	10.1	800 × 1200	0.170	1.04	557	536
Tablet4-LCD	7.0	800 × 1200	0.118	0.811	457	563
Tablet5-LCD	9.7	1536 × 2048	0.096	0.882	523	593
WS-5MPLCD	21.3	2048 × 2560	0.165	3.86	842	218
WS-3MPLCD	20.8	1536 × 2048	0.207	1.64	332	203

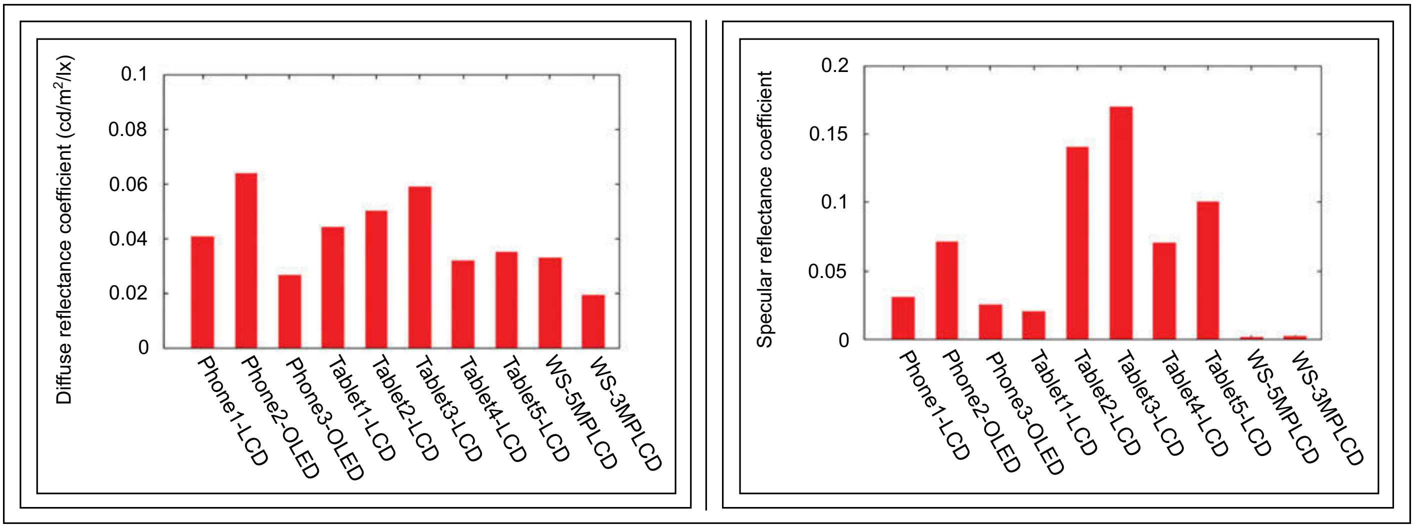

Fig. 1: Shown are the diffuse reflectance coefficients (left) and specular reflectance coefficients (right) for the devices tested in this study.

exhibit a diffuse reflected luminance in the range of 1.0–1.5 cd/m^2, and some handheld devices will reflect up to 3 cd/m^2, reducing (or negatively impacting) the useful range of luminance response.

However, these measurements rely on methods developed for workstation gray-scale monitors, and thus more studies are needed to fully understand the effects of ambient illumination on handheld image quality, including the effects of light-source spectral content and angular distribution.

Spatial Resolution and Noise

The description of the strength of signal-and-noise transfer at different spatial frequencies is a useful indication of the response of the display device to image content. Resolution and noise are typically characterized using the modulation transfer functions (MTFs) and noise power spectra (NPS) measured with an imaging photometer off a pattern on the screen. Using methods recommended in Ref. 9, we used a horizontal or vertical 1-pixel line pattern in a uniform background captured with high magnification by the photometric camera.

Figure 2 shows captured images displaying the 1-pixel line on each display. The subpixel shapes and layouts on the Phone2-OLED and Phone3-OLED with PenTile technology are different from those seen in LCDs. WS-5MPLCD, the only monochrome display in this study, has each subpixel at almost the same luminance value and the MTF is the closest to that of a square signal pattern.

Figure 3 shows MTFs as a function of absolute frequency in the horizontal and vertical directions for all displays. The horizontal MTFs of almost all tablet displays and the vertical MTFs of all handheld displays are higher than the MTFs of workstation displays. As seen in Fig. 1, the resolution characteristics of the display devices are affected by the symmetry of the pixel addressing scheme for the R, G, and B subpixels. In addition, the noise performance of handhelds is superior to that of the medical displays, as seen in Fig. 4,

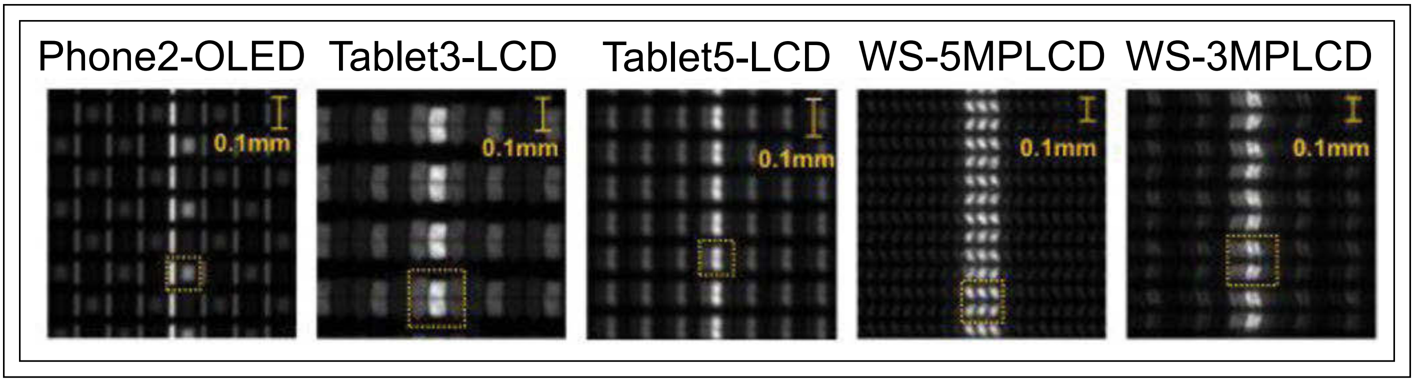

Fig. 2: Each screen displays a 1-pixel line pattern that was captured by a photometric camera. Since these images are not exactly in the same scale, 0.1-mm-scale bars are indicated. Squares bounded by orange dotted lines show the 1-pixel region of the displays. The vertical lines reflect the horizontal resolution characteristics corresponding to the RGB direction.

which shows 1D NPS in the horizontal and vertical directions for all displays.

A detailed analysis of the results on resolution and noise should take into consideration the fact that handhelds are not seen at the same viewing distances as workstation medical monitors, nor are they seen in a "static" fashion, *i.e.*, the angle of viewing is changing and can be adjusted by the viewer. All measurements reported in this article were taken at a normal viewing direction, perpendicular to the display face. This, along with possible degradation due to motion of the device while in use, are areas of current research in our laboratory.

Promising Performance, But Further Research Required

Although not covered in this article, other aspects of display performance are quite relevant for handheld medical image viewing, including temporal response, the effect of device motion on image quality, and the potentially rapidly varying viewing conditions. In summary, handheld displays can have good spatial resolution and noise characteristics compared to medical workstation displays. Since the luminance characteristics of the handheld display might not comply with the GSDF response, the displayed image contrast can be different from that of images radiologists and medical staff are familiar with from their workstations. Further investigations that rely on visual studies and take into account all relevant factors are needed to determine the reliability of the handheld device as an image viewing platform for demanding medical imaging applications.

Acknowledgments

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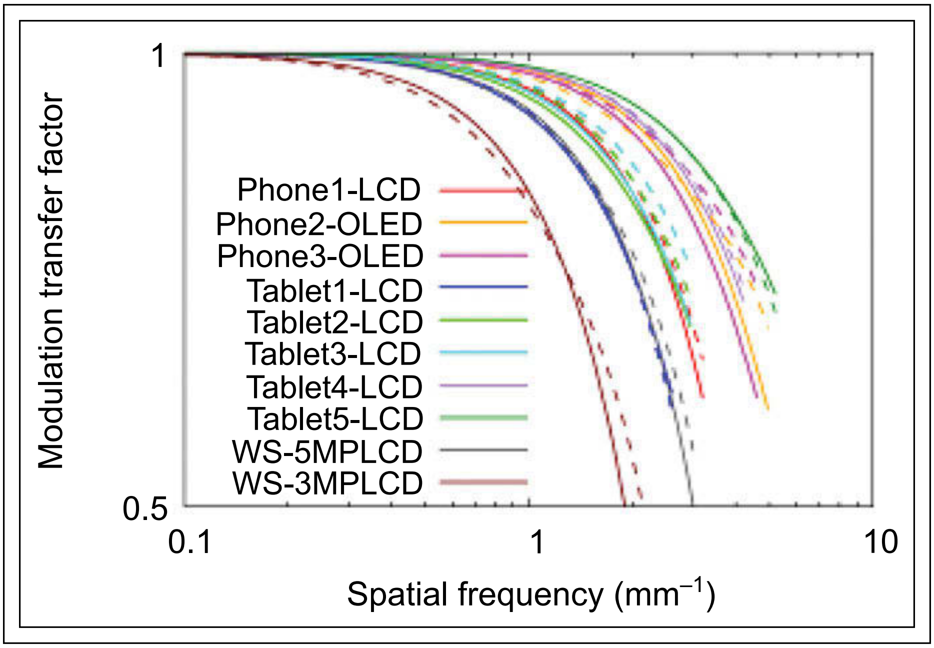

Fig. 3: Modulation transfer functions are shown as a function of absolute spatial frequency in double-log-scale mode for the devices tested in this study. Solid (dashed) lines are for measurements in the horizontal (vertical) direction.

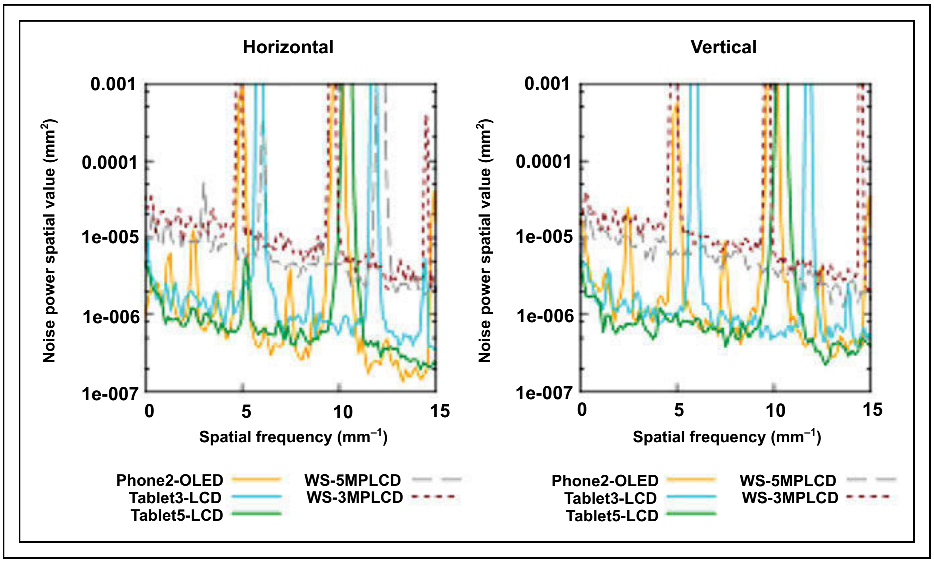

Fig. 4: One-dimensional noise power spectra are shown above for the devices tested in this study.

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Vehicle Displays & Interfaces Symposium Celebrates 20th Anniversary

SID's Metro-Detroit Chapter will present its 20th annual Symposium on Vehicle Displays & Interfaces October 10 and 11 at the University of Michigan-Dearborn. The Detroit Chapter, with physical roots in the center of U.S. automotive manufacturing, sponsors this symposium to bring together scientists and engineers from the display, photonics, human–machine interface (HMI), and vehicle systems communities.

The Vehicle Displays & Interfaces Symposium is an essential event for anyone wishing to understand the ongoing evolution of displays and interfaces in vehicles (a short history appears at www.sid.org/Chapters/Americas/metrodetroit/history.aspx). This year, papers will be presented on the automotive market, vehicle displays and lighting, human/vehicle interfaces, advanced display technology for vehicles, and other vital topics for automotive HMI design. New for 2013 is a poster session on HMI technology and applications, with an emphasis on student and university work.

Last year's Symposium celebrated the 25th anniversary of the Detroit Chapter (Fig. 1–3). It was sponsored by Continental, DENSO, and Yazaki. This year's event will offer (in addition to the technical presentations), tutorials, an exhibition, keynotes by automotive industry notables, and more. For information, see: http://www.sid.org/Chapters/Americas/MetroDetroit.aspx.

– Jenny Donelan

***Fig. 1:** Participants at least year's symposium take in a tutorial titled "Behind The Scenes – Cadillac Cue Design" by Mike Hichme, senior manager at GM Design.*

***Fig. 2:** Another highlight of last year's symposium was a panel discussion on "How to Achieve High Performance Low Power Automotive Display Systems." Pictured are Jason Thompson (Texas Instruments) at the lectern and, from left: Mark Larry (Ford), Silviu Pala (DENSO), Nick Colaneri (ASU), Alban Lescure (Microvision), and Bruce Dinda (Kyocera).*

***Fig. 3:** Continental's 2012 exhibit featured integrated display technology.*

Start-up Fundamentals

A game-changing idea is only one of the ingredients you will need to launch a successful new business. Without the right team and a commitment to ongoing fundraising, your brilliant new venture will founder. This article is the first of four in a series by a venture capital expert who has both launched and funded new companies.

by Helge Seetzen

YOU have an idea. It's incredible. It will change the world. Generations will laud you as one of the greatest of your chosen industry, an industry you will revolutionize and disrupt. Your idea is so awesome that it's hard to put your excitement into words. And your idea will fail.

At least that's statistically the most likely outcome. According to the Association of University Technology Managers (AUTM), over 90% of university inventions go nowhere. And since AUTM is effectively the lobby of the people charged with the commercialization of inventions, those are probably optimistic numbers for university inventors. Inventions from private individuals almost certainly do worse.

Before we can talk about fundraising and venture capital, the last stages of the initial venture formation process, we need to look at the technology-transfer chain as a whole.

Helge Seetzen is CEO of TandemLaunch Technologies, a Quebec-based company that commercializes early-stage technologies from universities for its partners at major consumer electronic brands. He also co-founded Sunnybrook Technologies and later BrightSide Technologies to commercialize display technologies developed at the University of British Columbia. He has published over 20 articles and holds 30 patents with an additional 30 pending U.S. applications. He has a Ph.D. in interdisciplinary imaging technology (physics and computer science) from the University of British Columbia.

Invention *vs.* Innovation

Technology transfer, the process of taking concepts from idea to product, requires two very distinct steps: invention and innovation.

Let's start with invention. Invention is an intellectual exercise in connecting the dots. It's the eureka moment when you connect multiple problem statements with existing solutions from other spaces, parallel or unrelated, and come up with a new combination of thought that solves a problem you have discovered. It is a mental event.

Invention can be an ongoing process or a clearly defined moment. An example of the latter was the genesis moment for my past start-up, BrightSide Technologies. We had been working on combining two LCD screens to achieve high contrast. Unfortunately, each screen absorbed over 90% of incoming light, so the dual layer was extremely inefficient. We had thought about using an array of tiny light sources instead of the first LCD but couldn't think of any practical device that could deliver millions of such tiny light sources (this was a decade ago, when large-scale OLED was still a vague dream). We brought in a photography researcher who showed us a camera concept that would overlay a blurry and an adjusted sharp image to get much higher dynamic range in image rendering. Eureka! We could use the same blurry + sharp idea on the display side by employing an array of big LEDs (1000× larger than the tiny light sources that we thought we would need). In that distinct moment, local-dimming LED TV was born (and a start-up formed around it).

For simplicity, let's call the invention-rich period "research" and the people doing it "inventors." An inventor then is a person who synthesizes the problem statement and solutions into a novel concept. One of the best macro-scale models that we currently have for fostering this process is the university, though the same definition applies to independent inventors. Universities provide the most open and free environments for research to occur, with, by a wide margin, the most financial resources (Fig. 1). These definitions of invention, research, and inventors are completely indifferent to what you do with the invention afterwards; you can be an inventor and not have done anything at all other than the mental exercise.

The Entrepreneur

Generally, however, someone wants to do something with the idea. That's where the innovator comes onto the scene. Innovation is the ongoing process of getting an invention to a point where it has an application value of some kind. That doesn't happen automatically because technology is only useful if somebody uses it. Unlike knowledge, technology doesn't have any intrinsic value. If you discover that a distant object in the sky is a planet, that knowledge has some abstract value for humanity. If you find a cure for cancer and it doesn't teach you anything new about biology, or the human body, and is just

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a particular mix of stuff that works, then it has no value until it actually cures somebody's cancer. (See the sidebar.)

Innovators pursue what we often call development – the act of rapidly risk-reducing an idea emerging from research, as well as reducing the idea to some practical implementation. Outlier or extreme cases are considered, many of the scientific elements must be validated, and the fundamentals of how a new technology works will be tested and mapped out. In other words, at this stage, the technical risk of an invention not working are eliminated or largely brought under control.

Innovators work all over our industry – many of them in the development departments of large display companies where they consistently turn ideas into great devices for us to admire at shows like Display Week. But sometimes that isn't enough. Sometimes, those ideas fall outside the scope of traditional development departments or live beyond the near-term roadmap of big public companies. That's when start-ups find their role in the economy and we encounter our third actor in the tech transfer process: the entrepreneur.

Entrepreneurs are innovators with limits. They drive innovation in a constrained environment where time, money, and resources are significantly lower than the requirements of the process seen at face value. An entrepreneur's job is to maintain the environment that allows innovation to occur by engaging in an aggressive pursuit of growth under conditions of risk.[1] This is what start-ups do best, due to their focus, speed, and flexibility. Start-ups are thus sometimes the point of invention, but more often than not they are created by entrepreneurs after the invention to act as innovation engines.

To create those engines, our intrepid entrepreneur needs pistons (people) and fuel (funding). A bit later, a healthy dose of lubricants must be added to the engine to keep it from blowing up, but we will ignore those operational aspects for now. Finding good people is hard and so is raising money. Fortunately, the two parts usually come in pairs. Good teams can almost always raise money fairly quickly – money generally follows talent. So the first goal for any entrepreneur isn't to raise money but rather to build a fundable team.

[1]Risk isn't the goal, but the inevitable consequence. An entrepreneur tries to achieve more than the conventional bar set by the limited set of resources, time, and money available. That's only possible if you take risks.

As research and knowledge become perhaps the **most crucial components to generating economic growth** *and competitive jobs in globally-linked markets,* **universities emerge as a key factor in determining the future** *well-being of the country.*

DAVID AUDRETSCH
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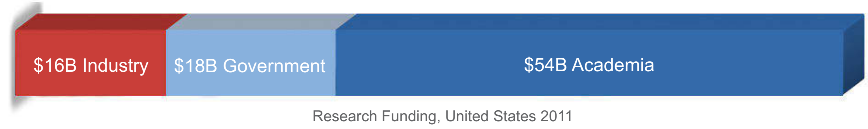

Fig. 1: *Universities dominate the invention space in the United States, as shown above. Source: TandemLaunch Technologies.*

Completing the Team

A strong team requires a good mix of skills, as well as a strong interpersonal fit between the founding team members. Most professional investors will tell you that team friction is the number one reason for start-up failure. Start-ups usually do not simply run out of money. They either implode due to internal conflicts or lose the ability to raise longer-range financing (usually also due to internal conflicts). Of course, some businesses are just plain unsustainable, but, in general, a good team can pivot to new opportunities, whereas a good business will fail utterly if the team collapses. Score one for the team, zero for the business model or technology.

Teams represent the bulk of value in a technology start-up: know-how about the business model, technology, and market. This know-how is often hard to characterize because it is the knowledge embedded in the heads of your people, but it is of enormous value to any potential acquirer and essentially for the operation of most revenue streams. The first step to forming a strong team is to fill the three principal roles needed for any tech start-up: hustler, builder, and plumber:

1. ***Hustler (CEO):*** The hustler identifies revenue opportunities and relentlessly hunts them down – including the early-stage financing, which is after all just revenue with equity debt attached. At a later stage in the growth of the company, it is possible to have an inward-focused CEO who emphasizes staff development and processes. Early on, that's a very difficult arrangement to pull off. For better or worse, the technology investment community got used to CEOs who are externally focused and full of (visible) energy. If you are a technologist who isn't fond of traveling and making constant presentations, I would strongly encourage you to find a business partner who is.
2. ***Builder (CTO):*** Your CTO is the builder of the central value proposition of the company, be it technology, product, or service. This role needs an innovator, not an inventor. You need access to inventors to get clarity on their thoughts, but that can take the form of a consultancy or advisory role. What you really need is an innovator who has enough understanding of the technology and commercialization process to drive the technology from invention to commercial application. This is the person who can communicate technical strategy (including to non-technical audiences such as investors and customers), motivate your technical team to deliver on this strategy, and formulate technical directions that lead to value creation.
3. ***Plumber (COO):*** The plumber keeps the place running, which can mean human resources, finance, operations, or literally ensuring that everybody on the team is fed. If you have the right hustler and builder, they won't have much time to support these activities. That said, this is definitely the most optional role of the three, at least for the early stages of a new venture. If you don't want an early stage plumber, or can't find a good one,

then I would recommend outsourcing these activities to somebody other than the hustler or builder (*e.g.*, hiring a junior administrative staff early on, using financial service consultants, *etc.*).

Titles are of course a matter of choice in a start-up. Still, these three roles cover the fundamental elements of any seed-stage company. Companies that lack a hustler at the helm will rarely scale – often condemning themselves to eternal “in the basement” status with essentially self-employed founders just getting by on subsidies and modest revenue. Similarly, the confusion between inventors with innovators for the CTO role is, in my experience, the dominant cause of failure for university spin-outs – the professor (almost always an inventor) stays in charge and after a few years everybody wonders why no product was ever launched.

Finding people with the above skills is a great start, but not quite sufficient to celebrate the success of your new venture. These people also need to work well with each other and, more importantly, do so in an environment that will be as stressful as any they have ever encountered. Think of your co-foundership as a marriage without a pre-nuptial agreement and few social conventions. Your founding team thus needs a solid platform of common goals and values.

Start-ups typically fail due to a misalignment of interests, so you need to make sure right out of the gate that all founders have equal interest. It doesn’t do you any good to have two superstar entrepreneurs if one of them wants to build the next Facebook and the other wants to build a company to flip it for a million dollars in as short a time as possible. Right around the time you hit that million dollar milestone and get the first offer, that founding group is going to implode.

Co-founders also need to have similar emotional ownership of the venture. In other words, they should feel bad if things are not going well, as that’s the only way that your founding team will really pull out all the stops to make things better. In this context, it is usually also a very bad idea to have co-founders with different time commitments (*e.g.*, one of them still working elsewhere). Investors hate founders who are not “all-in,” for good reason, so you need to make sure that your team is fully committed. Finally, try to avoid “single task” co-founders. Your controller isn’t your co-founder, nor is your first software developer. You are looking for people who are first and foremost leaders. They might be technical leaders but they shouldn’t be just writers of code (or just accountants, etc.). That might work very well early on, but introduce great stress when your venture scales and you have many coders but only one genuine CTO.

Research to Innovation: A Tricky Transition

The transition from research and invention to development and innovation is a non-trivial topic all by itself. It is not always easy to overcome the traditional hurdles involved in going from the open, research-supporting, loose environment of universities to the focused, aggressively paced, agile, and risk-financed environment of innovation. A later article in this series will explore some options for inventors to use in order to facilitate this process.

Raising Money

The engine is ready. Time to inject some fuel. To do so you need to know where the money is and how to get it. There are many different types of investors, and the second article in this series will go into the details of different investor types, their financial reward models and expectations, and some specific strategies to raise money from each type. For now, let’s deal with the most basic case of a seed investor: private money without a specific emotional connection to the entrepreneur (*i.e.*, not your rich cousin). These people are often called angel investors, though I have never fully understood whether they are guardian or vengeful angels. I have seen both variants during nine rounds of fund raising as an entrepreneur and I am sure that I show both sides now that I am sitting on the other side of the investment table.

We have already established that almost all investors bet on people – teams of people specifically – so that takes care of much of the value proposition of your pitch. Still, raising money is not quite as easy as just showing up with a good team. I have made hundreds of investment pitches. And yet I have only closed about 50 investors over the years (individuals and institutions). While that’s still a lot of money, the conversion rate from pitch to investors is depressingly low, with maybe one in ten pitches going anywhere.

Fundraising Is Fundamental

The key to fundraising is to understand that it is a function like any other. Consider giving somebody the title of Vice President of Equity Sales. Because that’s what fundraising is – sales of a product (equity) with all the traditional aspects of a sales program: lead generation, qualification, cold and hot calling, relationship management, and, ultimately, lots of shoe-leather abuse. In that sense, fundraising is just as much a functional skill as software development or product marketing. If your start-up plans multiple investment rounds, then I would strongly recommend that you staff accordingly (add the matching experience to the requirements for your CEO hire if possible). Fundraising cannot just be something that you do “on the side” – you will either run out of cash or get taken advantage of so badly by savvy financial operators that you will wish you had run out of cash.

Fundraising is also a continuous process, even if you actually do it in trenches. There is a common misconception that fundraising is something you start when you need the money and then stop when you get it (until you need it again). That never really works. Investors need an ongoing relationship and it is your job to maintain it, especially during times when you don’t need their money. If the first email from a CEO after a funding close is a request for more funding, often a year later, there is little chance of success. A monthly or at least quarterly investor letter is really a must in these times. Really savvy companies will go as far as creating online dashboards for their investors, but that’s definitely in the optional camp.

The need to be in constant fundraising mode can also have some positive benefits for your organization. Fundraising is often the only external metric for a pre-revenue technology start-up. It forces you to achieve milestones and make meaningful progress toward your end goal. It will push the team to the limit and certainly added some dog-and-pony-show pressure, but ultimately build the best value for everybody involved.

As a final note on fundraising, I recommend to be prepared to be lucky. You ultimately cannot control all the variables in your venture or fundraising process. Instead, you need to create a foundation where bad luck won't kill you and good fortune can be leveraged. In the fundraising game, this means to always have a backup plan if the "sure thing" investment doesn't materialize and at the same time to keep an open eye for opportunities out of left field.

As is probably obvious by now, entrepreneurship is not for the faint of heart. Building a technology business requires a strong team, deep innovation, and usually quite a lot of money. Even if you assemble all of these elements, your venture is still more likely to fail than to succeed. But once in a while it all just works. The product inspires the world, the bankers love you, and the team can't stop hitting home runs. In these moments there is no better role than that of the entrepreneur!

The next article in this venture capital series is about different investment models and how to use them. ■

Direct-Dry-Film Optical Bonding: Finding New Applications

Originally developed for avionics and military displays, Direct-Dry-Film (DDF) optical bonding is now moving into industrial and consumer applications such as touch screens, TVs, smartphones, tablets, digital signage, and medical imaging.

by Birendra Bahadur, James D. Sampica, Joseph L. Tchon, and Vince P. Marzen

OPTICAL BONDING in display products was first used for CRTs and then for flat-panel LCDs around 1980. The technology was confined mostly to low-volume high-performance avionics and military displays for a long time afterward. During the last 6 years, optical bonding has exploded in many commercial and industrial applications, such as iPhones, touch screens, tablets, digital signage, and medical imaging.[1-4] Optical bonding has grown to a multi-billion (~ $2 billion) industry and is still growing at a fast pace.[1,2,4] Liquid bonding has been the most popular optical-bonding technology for many years,[1,2] but dry-film optical bonding is also gaining in popularity.[2,3]

Rockwell Collins started the optical bonding of LCDs in the late 1980s, using conventional liquid bonding.[1,2] Certain limitations of the technology (described later in this article) were realized during this period, which prompted the company to start developing dry-film bonding in 1993. During early developments, avionics products used a hybrid technology; *i.e.*, subassembly layers were bonded using optically clear PSA (dry film) and then those subassemblies were laminated to the display using liquid adhesives.[2] Since 2006, however, all of Rockwell Collins' avionics and military products, except legacy ones, have used dry-film optical bonding. The company realized the benefits of its Direct-Dry-Film (DDF) optical bonding [2,3] over conventional liquid optical bonding[1,2] for emerging commercial applications and decided to license the technology and provide optical-bonding solutions for a variety of consumer and industrial applications.[2,3]

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The Ins and Outs of Optical Bonding

Optical bonding is defined as the bonding of two or more optical components using a clear optical index-matched adhesive. In its simplest form, it fills the air gap between the cover glass and the display with an index-matched material that reduces the specular reflectance and increases the contrast of the display stack.[2] An anti-reflective (AR) coating is usually applied to the top surface of the cover glass, along with possibly an anti-smudge (AS, hydrophobic) coating and often an anti-glare (AG) treatment. These materials reduce the specular reflectance further and increase the display contrast and legibility significantly in high ambient lighting.[2,5,6] The optical bonding of many components reduces the total reflectance of the stack drastically. It also improves the environmental performance and structural integrity of the display stack simultaneously and provides design flexibility.[2,3,6,7]

The specular reflectance (R_S) of an interface between two non-absorbing media of refractive indices n_1 and n_2 is given by[8]

$$R_S = [(n_1 - n_2)/(n_1 + n_2)]^2 \,. \quad (1)$$

For a glass (n_1= 1.5–1.52) and air (n_2= 1.0) interface, R_S is ~ 4.0–4.25%. If two materials have identical or very close refractive indices, the R_S from their interface will be close to zero. Filling the space between two identical layers with index-matched adhesive cuts their specular reflectances to almost zero. This index-matching principle is widely used in optical bonding.

The simplest interference AR coating consists of a single quarter-wave layer of transparent material whose refractive index is the square root of $n_1 \times n_2$. For air and commonly used crown glass (n_1= 1.52), it comes out to be 1.23. The material having the closest refractive index with good physical properties for coating is MgF_2 (n=1.38).[8,9] Many layers of graded refractive indices may be used to fill the space between the two layers of significantly different refractive indices. Multilayer thin coatings with destructive interference for reflected light, such as high-efficiency anti-

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reflective coating, are used to cut the specular reflectance significantly.[8,9] Recently, developed "Moth-Eye" type AR films provide even better results.[9-11] A diffuse surface, using microstructures, reduces the specular reflectance but increases the diffuse reflectance. Sometimes a combination of AG and AR is used to reduce the white-shirt effect or front-surface image reflection by diffusing the remaining specular reflectance.[2] A circular polarizer (CP) is used to cut the specular reflectance in cases such as OLED, LED, CRT, and EL displays and touch screens. It cuts the reflectance from metallic and dielectric coatings very effectively, but also reduces the display luminance significantly.

Display Contrast and Legibility

The impact of various layers and optical bonding on the display reflectance and contrast ratio (CR) can be easily understood by examining Fig. 1 and Eqs. (2) and (3).

Figure 1 shows a typical backlit LCD with cover glass. R1, R2, and R3 are the reflected lights from surfaces S1, S2, and S3.[2,5] Each surface reflects ~4%. The specular reflectance is additive from every layer, so the total specular reflectance for un-bonded glass is ~12%. It is 8.2% for un-bonded good AR glass (R1= 0.2%, R2 = R3 ~4%). For optically bonded plain glass (R1 = 4%, R2 = R3 ~0%), it is 4% and for optically bonded AR glass, it is reduced to 0.2% (R1 = 0.2%, R2 = R3 ~0%).

The CR of a commercial backlit LCD, with on-pixel luminance (L_{on}) of 75 fL and off-segment luminance (L_{off}) of 0.30 fL, can be calculated using formula 2:

$$CR = \frac{L_{ON} + R_S \cdot S + R_{d-on} \cdot D}{L_{OFF} + R_S \cdot S + R_{d-off} \cdot D} \qquad (2),$$

where R_S is the specular reflectance, $R_{d\text{-}on}$ and $R_{d\text{-}off}$ are the diffuse reflectances of the on and off segments, and S and D are the specular and diffuse light components of the high ambient lighting. In the dark, S and D are both zero, so the display has a very high contrast ratio (250:1) and is quite legible. To simplify the calculations, neglect the diffuse reflectance and the equation becomes[12]

$$CR = \frac{L_{ON} + R_S \cdot S}{L_{OFF} + R_S \cdot S} \cdot \qquad (3)$$

Let us calculate the CR of the display in 2000-fC ambient lighting. It comes out to be 1.31 for un-bonded plane glass, 1.45 for un-bonded AR glass, 1.93 for optically bonded plain glass, and 18.37 for bonded AR glass.

The optical bonding of the AR glass increases the CR from an unreadable 1.45 to a very readable 18.37. To obtain the same CR (18.37) with un-bonded AR glass, one has to drastically increase the display luminance to 2969 fL from 75 fL, which is impractical. In practice, the glass-optical adhesive and adhesive-polarizer interfaces have very low specular reflectances (~0.035% and 0.015%, respectively), which generate a CR = 15.09. This is still a highly readable CR.

In real life, there are a few reflecting surfaces inside commercial TFT-LCDs. The color filter and black matrix contribute the most (~0.3–0.4%), while the other layers (polyimide, liquid crystal) add negligibly. The total specular reflectance from the display stack (AR glass, polarizer, LCD cell) comes out to be ~0.65%, which reduces the display CR to 6.62. Further reduction in CR may come from the diffuse surfaces and diffuse light contributions [Eq. (2)]. The maximum high ambient lighting is substantially higher for commercial avionics (8000 fC diffuse) and fighter planes (10,000 fC diffuse + 2000 fL specular). To achieve a high ambient CR of ~4–9, these applications require much higher luminance (~ 100–300 fL). Besides drastically increasing the high ambient contrast of the display, optical bonding also increases its luminance moderately by reducing the backward reflections.[2] It also eliminates the parallax issue observed in some air gap units.

Environmental Performance

As mentioned earlier, optical bonding also improves environmental performance and structural integrity and provides design flexibility. Some benefits include:

1. Impact and Shock Resistance: Optical bonding of a strong glass on top of the display increases its impact and shock resistance drastically. The impact and shock resistance of the bonded unit is much higher than that of an air-gapped unit,[2,7] as the adhesive layer absorbs the shock to some extent and the bonded cover glass and display front substrate together provide much better mechanical strength than they would separately. The impact tolerance increases with increasing cover glass strength and thickness. Bonding increases resistance to damage by vandals in outdoor vending and bank machines and increases drop tolerance in cell phones, *etc.* Proper glass bonding helps displays tolerate severe shock, vibration, and boot-kick impacts faced in military and avionics uses.[2,3] It reduces pressure (pen, finger) induced liquid-crystal deformations in LCDs. Optical bonding also enhances user safety by keeping shattered pieces together when glass breaks due to severe impact.

2. Improved Visibility at Low Temperatures: The air-gapped designs generally trap atmospheric humidity in between the cover glass/touch screen and display, which may affect display legibility at low temperatures due to vapor and ice condensations. Optical bonding prevents this degradation by filling the air gap with adhesive.

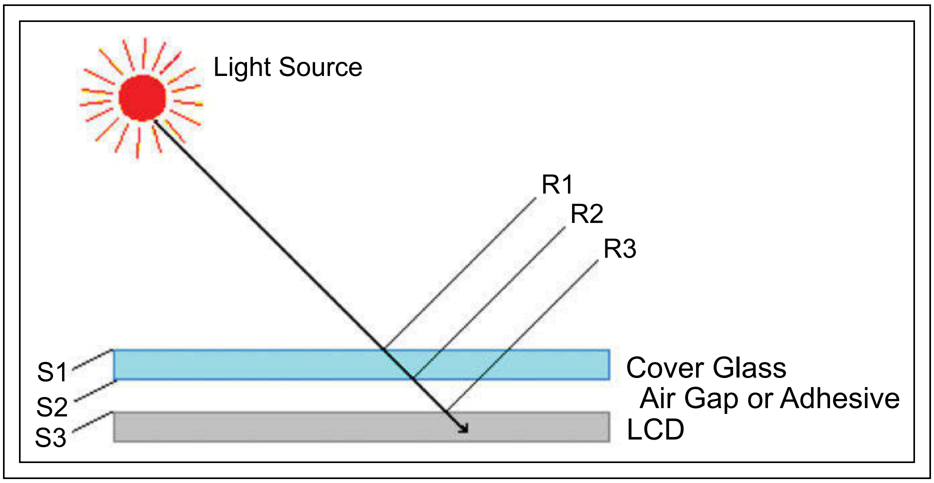

Fig. 1: Ambient light is reflected from an LCD with cover glass.

3. Improved Environmental Performance: LCD's iodine-based sheet polarizers deteriorate quickly in high-humidity and high-temperature conditions. The covering of the film's edges, top, and bottom by the adhesive in optically bonded displays improves the humidity/temperature performance of the polarizer and other optical films significantly. Many un-bonded displays fail the high-humidity/high-temperature and thermal cycling requirements of military and avionics products.[13] The adhesive covering also protects the polarizers from short-term accidental water contact.[2]

4. High-Altitude Performance: Optically bonded displays usually have better performance than un-bonded displays at higher altitude due to mechanical strengthening.

5. Design Flexibility: Optical bonding provides many design flexibilities such as narrower bezel and gaskets. The zero-bezel look of certain smart phones and tablet PCs is only possible by optically bonding cover glass to a pro-cap touch panel. Design capabilities such as these are not possible without optical bonding.

6. Added Functionality and Other Improvements: Bonding the display with appropriate complementary components such as touch screens, NVIS, ITO heaters, privacy films, and EMI and RFI absorbing layers can increase its functionality.[1,2 6] A display's solar and UV performance can be greatly increased by optically bonding it with solar rejection layers (IR filters, hot mirrors) and UV absorbing films.[2,6] Bonding of UV and low visible wavelength cut-off filters can drastically increase the life of some types of LCDs.[14] One example of this occurred when dichroic LCDs were used in direct sunlight in the deserts around the Persian Gulf. Those displays exhibited significant failures because proper UV filtering was not implemented.[14]

Optical Bonding and Adhesives

In liquid bonding, the adhesive is used in liquid form to bond the optical elements and is then cured by heat, light (UV or visible), chemical reactions, moisture, or a combination.[1,2,15–18] In the case of dry bonding, the optical adhesive is contained in sheet form and may or may not require curing.[2,16]

Bonding Adhesives

The sheet material used in dry bonding may be composed of either (1) fully cross-linked pressure-sensitive optically clear adhesives (OCAs) that do not require further curing[19] or (2) thermoplastics that can be reflowed at higher temperature and pressure and adhere after assembly, or (3) UV-curable sheets[16] that can be reflowed to take the shape of the bonding space and cured by UV later on. Acrylic and silicone are the two most commonly used materials in dry-film bonding.

Regardless of chemistry, process, and type of bonding used, the key characteristics of adhesives include the following attributes:

- Low (or ideally zero) birefringence
- Refractive Index = 1.47–1.52
- Low moisture absorption
- Low cost, readily available, non-hazardous ingredients
- Haze-less, optically clear (high transmission) and particle/defect free
- Resistant to thermal soak and cycling
- Good UV, IR, and life stability
- Nonreactive with glass and other optical films
- No out-gassing, bubble formation, or latent formations after bonding
- Flexibility for repairing products later on and removal of parts from partial assembly
- Superior adhesion to both high (glass) and low (plastics) surface energy materials
- Suitable for glass–plastic–glass laminations; various TCEs
- Processing temperature for bonding < 90°C

Liquid-Optical-Bonding Limitations

Liquid optical bonding (LOB) has been described very well by Mozdzyn and Rudolph,[1] Bahadur *et al.*,[2] and many commercial firms.[15] The main weaknesses of liquid-bonding technologies are

1. The material preparation is cumbersome, costly, and defect-prone. In two-part systems, the materials must be mixed thoroughly in ratios as prescribed by the manufacturer. The air and byproducts, generated due to mixing or chemical interactions, must be removed. The raw materials and mixture should be filtered to minimize the foreign materials. Proper dispensing is a must to remove the entrapped air. Depending on the automation and process used, ruggedizers need to develop some level of their own custom expertise. In general, lamination processes using liquid adhesives are labor intensive with long cycle times.

2. Radiation curing of UV-curable liquids can also be limited due to light-blocking masks and uniformity of cure affecting display performance over temperature.

3. A considerable shrinkage may take place during the curing of liquid adhesives, which makes the control of the bond-line quite difficult.

4. Many liquid adhesives, especially silicones, require a primer application to achieve adequate adhesion to many low-surface-energy substrates.

5. Liquid-optical-bonding processes are messy. The cleanup of display and tooling are essential after lamination. This significantly increases the cycle time and cost of equipment, material, and solvent; this can also lead to further yield loss.

Direct-Dry-Film Optical Bonding

Figure 2 shows the flow chart for DDF lamination. The first major step of the process is material preparation. Substrates must be thoroughly cleaned using conventional cleaning methods with automated or manual systems. The bonding process must be done in a clean room to avoid the particles and contaminations. The optically clear adhesive (OCA) is typically a sheet of adhesive with double-sided liners that is die-punched or laser-cut to the desired size. After material preparation, the OCA is roller laminated to the first substrate (aka cover glass) using a semi-automated machine commonly used for polarizer lamination. Once this is completed, the DDF bonding process involves three key steps inside a specially equipped chamber.

First, the OCA laminated cover glass and the rigid LCD are loaded into the chamber with a means to maintain a small gap in between them. The OCA faces the LCD front surface. A vacuum is subsequently induced to a desired level for a set time. The substrates are then allowed to fully contact each other while maintaining this vacuum followed by a method for applying external pressure via flexible membranes. To reduce the cycle time and improve the product flow, an autoclave is typically used to remove the vacuum voids quickly. The process and equipment are described in detail in several patents.[2,20] Depending on the configuration and chamber size, a takt time of 26 sec can be achieved. Further optimization of tooling and process may reduce it to <10 sec. The process maintains the LCD cell gap very precisely and

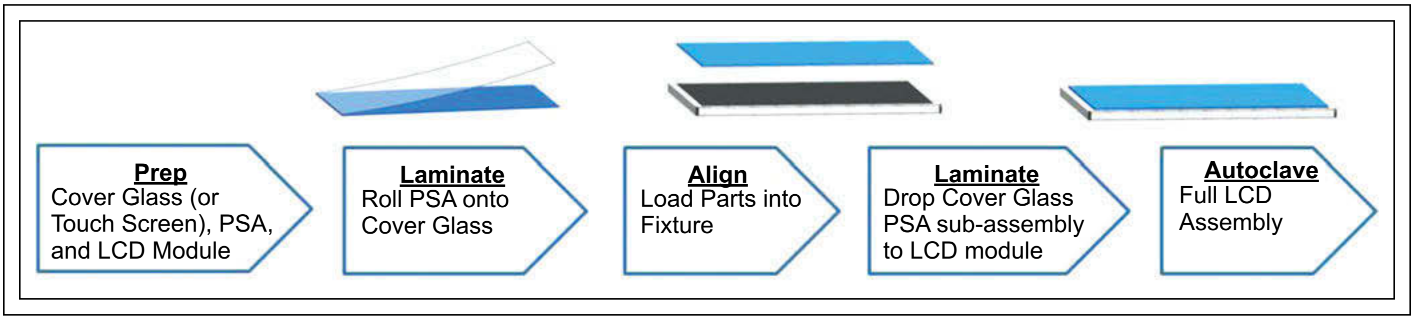

Fig. 2: The DDF optical-bonding process is shown from left to right.

creates no optical distortion or cell-gap non-uniformity. Materials to bond can include components such as AR glass, protective glass, touch screens, ITO heaters, NVIS filters, EMI shields, and even additional displays. These components can be bonded to the front/rear or both sides of a display or to another optical component.

Proper design, process optimization, and tooling are essential in producing a high-quality DDF optical bonding. Insufficient attention to detail in these areas will fail to achieve good results. The next section lists the advantages of Rockwell Collins' DDF bonding process in particular, and also clarifies some of the misconceptions about dry-film optical bonding.

Advantages of DDF Optical Bonding Over Liquid Optical Bonding

Some comparisons of dry-film bonding with liquid approaches are listed below:

- ***Cleaning:*** The overall process for DDF is much cleaner. The display is laminated without residuals to clean up after bonding and the tooling remains ready for immediate re-use.
- ***Handling:*** OCA is easier to handle than liquid optical adhesive because it is in sheet form.
- ***Adhesion:*** Dry film and liquid optical bonding both produce good adhesion.
- ***Material Usage:*** No wastage of optical adhesive due to spreading, leakage, and overflow. Cleaning solvents are not required. The DDF process is "green." The material utilization can be increased to > 80–90% by optimizing the use of the OCA sheet area for a few display sizes.
- ***Thickness Uniformity and Dimensional Superiority:*** The DDF bonding produces the required thickness and uniformity of the adhesive layer over the entire area because it uses the adhesive in a uniformly thick sheet form. The thickness control and uniformity is tough to achieve in LOB. Sometimes, liquid adhesive may overflow, leaving some parts of the gap unfilled. In DDF bonding, there is no need to account for shrinkage, bond-line control, or varying cure rates that can influence bond line and internal stress.
- ***Productivity:*** The overall productivity of the DDF process is much better than liquid optical bonding. It is much faster and simpler with fewer steps and less equipment.
- ***Automation:*** It is much easier to automate because the materials are solid; no mixing, de-airing, or pouring.
- ***Yield and Reparability:*** The process produces high yield and is repairable, which is not the case with some liquid-bonding technologies. It is difficult to repair the field-returned liquid optically bonded parts.
- ***Simultaneous Bonding of Multiple Components:*** Multiple components may be bonded simultaneously, which is not possible with LOB. This also reduces the bonding cost significantly.
- ***Cost:*** DDF optical bonding is cheaper than LOB in mass-scale manufacturing.
- ***Bonding Different Types of Components:*** DDF is the ultimate bonding technique for flexible (soft) to soft and soft to rigid (hard) surfaces. In hard-to-hard bonding, the properly developed techniques, optimized processes, and improved materials produce equally good or better results than those produced by LOB, which is better for bonding curved and uneven surfaces.
- ***Size and Large-Area Bonding:*** The DDF process works very well from small–to–large sizes. It has been scaled up to a 65-in. TVs.[3] Larger tooling may be quickly fabricated to support larger sizes when the demand arises.
- ***Environmental Performance:*** DDF-bonded displays exhibit better environmental performance (vibration/shock and temperature) than LOB displays. They show no delamination at elevations >100,000 ft.

DDF Optical-Bonding Applications

DDF optical bonding is becoming popular in industrial and consumer applications that require outdoor readability and durability to withstand impact, vibration, extreme temperatures, altitudes, dust, and rough handling. This methodology also integrates touch screens very effectively. DDF optical bonding provides the following attributes to displays:

- Enhanced sunlight readability (~5–10 times, depending on application).
- Increased impact resistance (~3–8 times depending on the bonded cover glass).
- High shock and vibration tolerance.
- Very low reflectance for touch screens in desired applications.
- Greatly enhanced life by protecting the display materials from the humidity.
- High-quality optical bonding of performance-enhancing auxiliary components, such as AR, AG, AR/AG/hard coat/anti-smudge and heater glasses, touch screens, and UV, NVIS, EMI, and sunlight filters.

Some particular optical dry bonding applications are listed below:

Military and Avionics: Military, ground vehicles, and avionics displays operate in

Fig. 3: *A variety of dry-film optical bonded displays are used together in this cockpit. Image courtesy Boeing.*

notoriously rugged conditions. Challenges include rough terrain, extreme temperature changes, high ambient lighting, high altitudes, electromagnetic interference, shock, and vibration. A Boeing 787 cockpit using many DDF-bonded displays is shown in Fig. 3.

Marine Electronics: Displays used in marine electronics, including ships and yachts, are regularly exposed to harsh environments such as high humidity/high temperature, high ambient lighting, salt water, rain, shock, and vibration. DDF bonding helps to satisfy these requirements. It also provides lamination capability for many displays on a single sheet of large glass, which is often desired in yachts (Fig. 4).

Fig. 4: *Direct-dry-film bonding works well for combining multiple LCDs on one sheet of large glass, as is often desired in luxury yachts. Image courtesy Kessler–Ellis Products.*

Medical and Other Applications: Medical displays require mobility, sharp pictures, touch screens, and reliability features in demanding environments with high ambient lighting, shock, vibration, frequent temperature changes, and sterile conditions. DDF optically bonded displays provide these attributes. Other potential applications for DDF technology include smart mobile devices with enhanced displays for better outdoor readability – a requirement well-suited to DDF optical bonding.

Branching Out

Optical bonding has been widely used in military and avionics for a long time, where it improves the optical as well as environmental and functional performances of a display stack. Liquid and dry-film optical bonding both fulfil the requirements of most of today's new applications. DDF optical bonding is superior in many ways to the more popular liquid optical bonding in optical and environmental performances as well as cost, material usage, and volume production. It is a highly "green" technology and is growing very fast in numerous applications.

Acknowledgments

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New Transparent Conductors Take on ITO for Touch-Screen and Display Applications

Indium tin oxide (ITO), a transparent conductor, has been a staple of flat-panel display manufacturing for decades and has been in great demand from the growing touch-screen industry. Limitations of cost and performance, as well as concerns over availability, have led to the search for a replacement material. Several candidates exist or are in development, but none have yet gained the scale to displace ITO.

by Paul Semenza

TOUCH screens, LCDs, thin-film solar cells, and other devices require the creation of electrodes on a substrate (usually glass or plastic film) that are both transparent, so as not to block light through or from the display or to the photovoltaic material, and highly conductive, to optimize power consumption and sensitivity. As if finding a material that can provide optical transparency and electrical conductivity were not challenging enough, flexibility (as in bendability), ease of manufacturing, and, of course, low cost are also requirements.

ITO: Challenged, But Still the Dominant Transparent Conductor

The material used for the vast majority of transparent conductors is indium tin oxide (ITO, typically 90% In_2O_3 and 10% SnO_2 by weight). ITO is the most prevalent example of the class of transparent conductive oxides, which can also include nitrides or fluorides (*e.g.*, TiN), as well as ZnO and CdO. Doped oxides include In_2O_3:Sn (ITO), ZnO:In (IZO), ZnO:Al (AZO), ZnO:Ga (GZO), and SnO_2:F (FTO); mixed oxides include In_2O_3–ZnO, $CdIn_2O_4$, and Zn_2 SnO_4.

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Indium is a rare-earth metal, typically extracted as a by-product of zinc or tin mining. As such, there have been supply and pricing concerns. Supply concerns have been alleviated to some extent by the development of new mines and recycling, but given the concentration of mines, political conflicts, such as that in 2012 between China and Japan over the East China Sea, have the potential to threaten supply. Indium pricing has also been highly dynamic, ranging from \$200 to \$1000/kg; recent prices have been around \$500/kg.

The manufacturing process for ITO also impacts costs. Magnetron sputtering, the process typically used for ITO deposition, can involve material wastage of more than 50% and is energy intensive. The temperatures needed for crystalline alignment of ITO film are close to the melting point (250°C) of PET, the most common film. Some ITO film makers are developing transfer methods to improve efficiency.

In addition to cost and manufacturing issues, ITO has performance limitations. ITO is transparent, but often has a yellow tint. Its refraction index is 2.0 (depending on the process and density), which is higher than glass (1.4) and PET (1.4–1.6), and means that high reflection values are commonly encountered and even total internal reflection of passing light is possible. To increase conductivity, increased film thickness is used, which can result in etching marks. Finally, ITO is brittle and subject to cracking, especially under conditions in which the film is actively flexed, but can also crack due to stretching during the patterning or lamination process, especially with ITO film.

Despite the cost and performance limitations, ITO is the dominant form of transparent conductor and has an established supply chain, including targets, sputtering, substrate, and patterning processes. As shown in Fig. 1, ITO film capacity was over 20 million m² in 2012 and will increase by a third in 2013. Because of the high volume of flat-panel displays and touch screens that demand transparent conductors, replacing ITO requires stable and qualified material sources and mature supply chains, including deposition (coating) and patterning processes.

Several New Materials Vying to Replace ITO

Several different approaches are under development for the mass production of high-performance transparent conductors at low cost. Rather than using transparent oxides, these approaches tend to utilize advanced processing of common materials such as silver or advanced materials such as polymers or nano-

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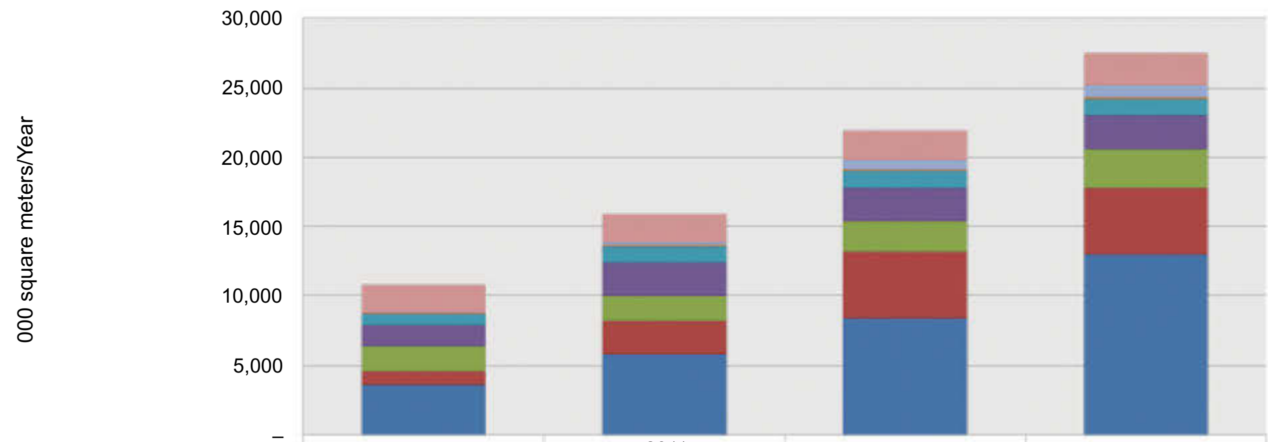

	2010	2011	2012	2013
Others	1,990	2,005	2,100	2,330
LG Chemical	50	200	680	840
Maxfilm	70	80	120	120
Teijin Chem	800	1,200	1,200	1,200
SEKISUI NANO COAT TECHNOLOGY	1,500	2,400	2,400	2,400
Oike Industries	1,800	1,800	2,200	2,800
Gunze/Junhong Industrial	1,000	2,400	4,800	4,800
Nitto Denko	3,600	5,800	8,400	13,000

Fig. 1: *ITO film capacity is expanding to meet the increased demand for touch screens (Source: DisplaySearch Touch Sensor Market and Evolution Report, 2013).*

tubes. Each of these approaches has features and limitations (Table 1); in addition, the level of process maturity and supply chain also vary greatly.

In addition to a stable supply chain, new materials must prove that they are superior to ITO in performance. There are several important factors in determining which materials can reasonably challenge ITO. Requirements for touch sensors include electrical conductivity, optical transmittance, material stability, and mechanical features (such as bendability and flexibility).

Metals are excellent conductors, of course, but not generally transparent. However, transparency can be achieved through the use of very thin (<10 nm) foils or by using certain patterns or structures. A metal mesh can be made from highly conductive metals such as copper or silver with very fine lines or particles (<5 µm is not visible to human eyes) in a grid pattern. If the metal lines make up 1% of the area, it is possible for the grid to have high transmittance. The electrical conductivity is related to the grid density or line thickness and can be less than 50 Ω/sq. for notebook PC sizes. Line widths of 10–20 µm are typical, with gaps of several hundred microns. The regularity of the grid pattern in metal-mesh touch sensors can lead to diffraction (moiré) patterns when overlaid on a display with a regular pixel structure, particularly when the display is >300 ppi, so the metal-mesh pattern is often rotated at an oblique angle.

Instead of the grid pattern of metal mesh, nanowires have a random alignment. The diameter of nanowires is 20–100 nm; thinner wires enable higher transmittance but are more difficult to make. The density of nanowires decides the sheet resistance (higher density results in lower resistance). Copper (approximately \$10/kg) is much cheaper than silver (\$800–1000/kg – and silver nanowire ink is about 10 times that of silver), but copper nanowire in ink solution has a much higher production cost. Silver nanowire has excellent conductivity, transmittance, and flexibility. Silver nanowires or nanoparticles can be formulated by $AgNO_3$ reduction, a form of ink.

Organic materials, including conductive polymers, carbon nanotubes, and graphene, can also be used for transparent electrodes. Conductive polymers are not as conductive as metal and ITO but they are easier to process and have lower material costs. In addition, their drying temperatures and other features make them more widely applicable to industrial uses. The most well-known conductive polymer is PEDOT (poly-3,4-ethylenedioxythiophene), which was invented by Bayer and commercialized under the name Baytron. While some conductive polymers can appear dark, PEDOT is light bluish (on the substrate) so that it is more suitable for use as for transparent conductive electrodes. Other conductive polymers are polypyrrole, polythiophene, and polyaniline.

Carbon nanotubes (CNTs) are allotropes of carbon (others are graphite and diamond) formed by atoms combining into tubular hollow cylinders, each one ~1 nm in diameter and 1,000–10,000 times as long. The single-wall format is a single layer; multi-wall is a nest-like structure in which smaller tubes are included in a bigger tube. In addition to the tube form, there are variations such as Canatu's nanobud, which looks like a tube

Table 1: New transparent conductors with the potential to replace ITO are being pursued by many companies. (Source: *DisplaySearch Touch Sensor Market and Evolution Report*, 2013).

Material	Pros	Cons	Makers
Metal Mesh	Low resistance: 0.1-30 Ω/sq.	Mesh can be visible and interfere with LCD pixels (moiré patterns); surface roughness is bad for OLED, PV; long design time	3M, Atmel, CIT, Fujifilm, Gunze, NanoGrid, PolyIC, UniPixel, Fujimori
Silver Nanowire; Nanoparticle	High conductivity/transparency; easy to use, inexpensive; established supply chain	Increased haze <30 Ω/sq.	Blue Nano, Cambrios, Carestream Carestream, Ferro, Saint-Gobain, Seashell, SVG; Cima NanoTech
Conductive Polymer	Inexpensive, solution coating	Low conductivity at acceptable transmission (resistance >100 Ω/sq.); bluish color; reliability affected by humidity	Agfa, Daicel, Heraeus, Kodak, Lintec, Nagaoka Sangyou, Oji, TDA Research
Carbon Nanotube	Robust and stable	Low conductivity at acceptable transmission (resistance >100 Ω/sq.); hard to wet-etch	C3Nano, Canatu, Eikos, LG Chem, Mitsui, SouthWest NanoTechnologies, TECO, Top Nanosys, Toray, Unidym
Graphene	Stable, reliable; bendable/foldable	Still in R&D stage	Bluestone, Graphene Square

with fullerene units on it. CNTs offer good optical and electrical performance. Flexibility and stability are excellent because of strong carbon atomic bonding. Generally, CNTs used for touch sensors look somewhat dark, and the sheet resistance is higher than ITO.

Graphene is a single layer of carbon atoms bonded in a hexagonal honeycomb crystal lattice. It has low light absorption (2.3%), high mobility (2×10^5 cm^2/V-sec; silicon is 1400 cm^2/V-sec), and low resistivity (1.0×10^{-8} Ω-m, lower than silver). However, its mass-production process and scale are not mature. Exfoliation has been shown to be effective, but it cannot be applied in large areas. Another method is to grow it on a metal substrate (Ni or Cu) using a process and transfer it to a film substrate.

Metal mesh and silver nanowire have started to be adopted in touch sensors, but the competition is only beginning. Material costs generally depend on production scale and generation method, and the coating or deposition method and patterning process have significant impact. In particular, the patterning process affects the desired touch-sensor specifications; for example, etching/silk printing is cheaper but still cannot compete with photolithography because the bigger line/space pitch cannot create narrow bezel designs. Ink-jet printing can achieve line widths < 10 µm and can combine coating and patterning, but only over small areas.

Don't Count ITO Out Yet

It is likely that ITO replacement materials will make an initial impact in large touch screens for notebooks and all-in-one PCs because cost is critical in these applications, and ITO provides good cost/performance in smaller touch panels and displays. Metal-mesh and silver nanowire/nanoparticle approaches have begun to compete for ITO replacement, and it is likely that other solutions will come to market soon. However, it is too early to declare that one or more of these approaches will significantly displace ITO; for that, material supply and production systems need to be developed to serve markets in the hundreds of millions of square meters. If one or more of these approaches can, in fact. be mass-produced at low cost, it is likely to enable a host of new applications for touch screens, as well as lower the cost of flat-panel displays. ■

continued from page 2

review of the display performance of four representative and commercially available tablet devices. Our second Frontline Technology article addresses the exciting potential of using commercially available tablets for medical imaging and diagnostics work. Author Aldo Badano and his colleagues at the U.S. Food and Drug Administration have conducted some very detailed studies into the optical performance of various tablet displays to determine which ones can produce performance equivalent to that of traditional medical imaging displays. Not only are the outcomes of this work somewhat surprising, but I learned a lot about the relevance of certain image-quality metrics and how they can be applied for this type of analysis. As Russel notes in his editorial, "When access to information is the primary goal of an information appliance, then tablets are the natural choice." Using tables to provide faster and more convenient access to medical imaging data, especially in non-hospital field settings, could really make an impact.

From Venture Capital to Optical Bonding, and Beyond

We've all heard the story: Guy with a great idea starts a small company in his basement (or garage for the Apple lovers). After a few years his invention succeeds beyond all belief and a large company pays him an unfathomable amount of money to commercialize the idea. Or, he builds his own company and becomes one of the dozen or so richest people in the world. Yes, it does happen.

I have had a few opportunities to work in the start-up company and venture-capital world. It's a great place, where ups and downs come like water from the tap and 9 out of 10 endeavors fail before anyone even knows what they were all about. Well, one of our own SID executive team members, Helge Seetzen, is also the CEO of a company that commercializes early-stage technologies. He's been at the helm of start-ups as a co-founder and now he helps guide start-up ventures through all the perils of the process. We asked and Helge graciously agreed to share his insights and experiences in a four-part series of articles focused on successful strategies for creating, funding, and growing new technologies ventures. The series begins this month with the first part titled simply "Start-up Fundamentals".

Another subject we frequently cover at *Information Display* is that of transparent conductors – all those niche technology innovations that are vying to take even a tiny share of the market from indium tin oxide. Some of them are starting to mature and seeing adoption in commercial products. It's not yet a revolution, but in some applications such as touch screens, companies are testing these alternative materials in the marketplace. Frequent *ID* author and well-known industry analyst Paul Semenza has taken a look at this marketplace and catalogued the various competing technologies and their developers for us in his Display Marketplace article titled "New Transparent Conductors Take on ITO for Touch-Screen and Display Applications." Paul has also clarified the debate over the availability and price of indium – a subject that almost everyone seems to have an opinion on. I think you will enjoy his concise analysis of this technology.

Right before we went to press, we heard from another analyst colleague, Jennifer Colegrove, who has also been collecting data on the transparent-conductors marketplace. Jennifer has done her own analysis on what the future revenue market might look like for some of the key competitors in this newly developing arena. We felt compelled to include her analysis as well, as a complement to what we had already planned, and therefore I hope you'll enjoy her column, "ITO Replacement Market Will Grow to $4 Billion by 2020."

Many of you have seen displays with optical bonding used in various ruggedized or direct-sunlight applications. This approach can help reduce reflections by eliminating the extra refraction indices between the face of the display and the safety panel or touch screen in the system. Most companies use processes that involve liquid chemistries such as urethanes, epoxies, or silicone gels. These processes are messy and hard to optimize. This month, author Birendra Bahadur and his team from Rockwell Collins describe for us their success in commercializing a process for bonding with pressure-sensitive adhesives (PSAs). In his article titled "Direct-Dry-Film Optical Bonding: Finding New Applications," Birendra explains how this method improves over the existing processes and which applications are best suited for this approach.

It was several months ago when I first suggested to managing editor Jenny Donelan that we needed a comprehensive overview of the business of displays in the various regions of the world. I was interested in seeing an analysis of the general dynamics of the regions, how the various customer markets work, and how the flow of products and technology differs from region to region. To get started, we chose to focus on three main areas: North America, Europe, and Asia. The result is this first installment of our Regional Business Reviews, "The North American Display Business Environment." Clearly, this is a hard topic to tackle and because of the extreme diversity of marketplaces that have evolved here, there is no one simple story to tell. However, there is a lot going on (over $143 billion in consumer sales alone) and I think you will find this a very enjoyable overview from which we will continue to mine important topics in future installments.

And so, as we bring this issue of *Information Display* to a close, we also have our regular SID News and Industry News features also written by Jenny Donelan. Jenny probably would have enjoyed a little more balance in her life this past month as she and our entire team worked hard to finish off this issue in the middle of a hot lazy summer in the northeastern part of the U.S. We hope you enjoy this issue and we also hope you can find time to put all your professional commitments aside long enough to enjoy life and savor some of the good weather and great outdoors. ■

ITO Replacement Market Will Grow to $4 Billion by 2020

An industry analyst is optimistic about the market for new types of transparent conductors.

by Jennifer Colegrove

ITO (indium tin oxide) is currently the dominant transparent conductor in the marketplace. However, due to ITO's high cost, long processing requirements, and fragility, non-ITO-type transparent conductors are gaining momentum. These transparent conductors may not only replace ITO, but also provide functions that ITO cannot. Transparent conductor applications include touch sensors, displays, lighting, thin-film solar (PV), smart windows, and EMI shielding. Touch Display Research forecasts that the non-ITO transparent-conductor market will grow from $206 million in 2013 to $4 billion by 2020 (Fig. 1).

Approximately, 10 types of ITO-replacement transparent conductors can be put into six categories: metal mesh, silver nanowire, carbon nanotube (CNT), conductive polymer, graphene, and other technologies. At the current time (2013), there are more than 180 companies and research institutes developing non-ITO transparent conductors or related technologies (Fig. 2).

Graphene is the most researched non-ITO material, with 41 companies and research institutes developing it. Carbon nanotube and metal mesh are number two and three, respectively. Twenty-nine companies supply non-ITO transparent conductive film, and twenty-one companies supply the nano ink or powder.

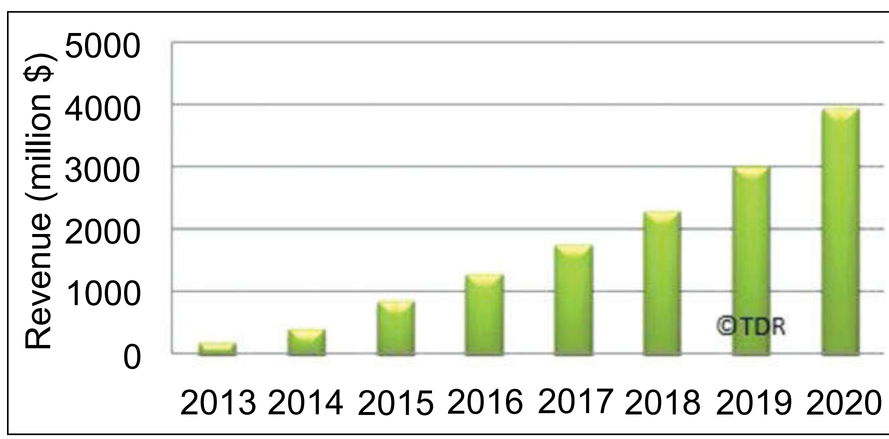

Fig. 1: The non-ITO transparent conductor market will grow steadily through at least 2020. Source: Touch Display Research, ITO-Replacement – Non-ITO Transparent Conductor Technologies, Supply Chain, and Market Forecast Report, *May 2013.*

There are many features to consider when developing or using a transparent conductive material, including sheet resistance, conductivity, cost, visual appearance, durability, and flexibility. Figure 3 compares cost and conductivity for the six major categories discussed above.

Fig. 2: Out of six categories of non-ITO transparent conductors under development (top rows in blue), graphene leads the pack, with more than 40 companies working on the material. CNT represents carbon nanotube. Source: Touch Display Research, ITO-Replacement — Non-ITO Transparent Conductor Technologies, Supply Chain, and Market Forecast Report, *May 2013.*

Transparent conductor	Companies and research institutes in 2013
Metal mesh	19
Silver nanowire	16
Conductive polymer	11
CNT	20
Graphene	41
Other TC technologies	10
Supplier of nano ink/powder	21
Supplier of TC film	29
Supplier of TC related equipment	15

Several companies are already producing these advanced transparent conductor materials. Atmel has been mass producing its metal-mesh touch sensor, XSense, for several

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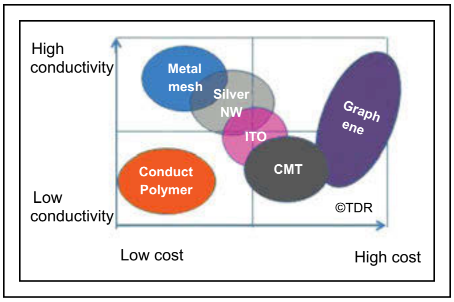

Fig. 3: Potential ITO replacements are compared in a cost vs. conductivity grid. Source: Touch Display Research, ITO-Replacement—Non-ITO Transparent Conductor Technologies, Supply Chain, and Market Forecast Report, *May 2013*

months. Fujifilm is currently expanding its EXCLEAR silver halide film capacity. UniPixel is starting the mass production of its metal-mesh UniBoss. Cambrios is leading the silver-nanowire transparent-conductor market. And conductive polymer has been used on displays for years. It will be interesting to see which non-ITO materials take the lead over the next 7 years and how much of the ITO market they will consume. ■

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The North American Display Business Environment

This article, the first in an occasional series that looks at business environments around the world, describes the historical, economic, and other conditions that affect display companies doing business in North America.

by Jenny Donelan

THE North American display industry is in many ways a paradox. A huge amount of display research and innovation takes place in this region, and a huge number of displays are purchased by its consumers. At the same time, a relatively small amount of display manufacturing is conducted in North America. Both these extremes are subject to exceptions, of course, and the strengths and weaknesses of the display industry in North America warrant a closer look.

Robust R&D

Display research and development are known fortes in North America. For decades, display discoveries have emerged from its universities and private companies, as well as from a smaller number of government-funded initiatives. Although this region does not have a monopoly on display discoveries, consider the recent inventions that have come out of North America. They range from fundamental scientific discoveries such as flexible backplanes, MEMs devices, quantum dots, and E Ink to practical applications of technologies that include 3M's quantum-dot films, many companies' optical bonding, multi-touch user interfaces from Microsoft and other firms, LED backlights, and more.

In ways both symbolic and actual, North America is also a kind of standard bearer for technology. It is home to many of the largest such companies in the world: Apple, Dell, Google, IBM, Intel, and Microsoft. These companies may not do the bulk of their manufacturing (if they do any manufacturing at all) in the U.S., but they are flagships that drive the computer and display industry rather than respond to it, and, in so doing, help shape worldwide trends.

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Retail Details

North America is also home to a huge consumer market, despite the fact that the standard of living in North America is not as high as that of some European and Middle Eastern nations. Consumers in North America are well-known voracious buyers of electronics. But they can be selective and ruthless in product choices – whether those be automobiles or mobile phones. And just because you sell popular products does not make you an automatic success – witness the demise of the Circuit City retail chain a few years ago. The Internet makes price shopping extremely accessible, and it's easy for consumers to compare products in ways that would not have been possible just a few years ago.

In addition, though they do buy eagerly, North American consumers are, in general, fairly saturated with "toys" and need compelling value or service in order make an electronics purchase. Consumers have grown a little cynical about new offerings (think of the tepid response to 3-D TVs), and unless you are a very clever innovator *and* marketer, like Apple or Samsung, it can be tough to entice consumers to continue upgrading through new product cycles. Consumers can also say one thing and do another: In the U.S., the idea of buying American-made products is popular, but when it comes to opening their wallets, consumers are driven more by prices and the latest trends than by country of origin.

Consumer confidence is another variable to be considered. Though the effects of recent legislation such as sequestration and the Affordable Health Care Act have yet to be seen in entirety, uncertainty about them can still have consequences. Parents waiting to hear if college loan rates will go up are less likely to invest in a new large-screen TV, and companies wondering how or if to revamp employee health insurance may hold off for a while on the purchase of new computer systems.

If your company is looking to break into the consumer market, whether as a retailer or a consumer-device developer, there are rewards to be reaped in North America, but you will not come by them easily. According to NPD DisplaySearch's Paul Semenza, "The end of the cycle – with retailers such as Best Buy or Amazon – is a tough business to enter but great once you get to it." In 2012, U.S. consumer-electronics sales totaled a hefty $143 billion, according to a report from NPD Group.[1] (By comparison, China's 2012 consumer-electronics sales were even higher – slightly over $200 billion in the same time period).[2] In the U.S., according to NPD, the top five consumer-electronics categories (all containing displays) were notebooks, flat-panel TVs, smartphones, tablets, and desktop computers. Best Buy, Walmart, Apple, Amazon, and Staples were the top retailers.

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Manufacturing Ups and Downs

For the most part, the manufacture of display panels takes place outside North America, with the lion's share of fabs in Asia. But there is display manufacturing of a different kind in North America – display integration. Says Semenza, "These are opportunities where some kind of customization is required – in the medical, military, and automotive markets, for example." Such customization includes optical bonding, rugged packaging, light-enhancement films, enhanced backlights, and so forth for a wide variety of applications. Examples of these are adding displays to autos and building units and integrating displays for the medical, military, and industrial markets, with the latter including digital signage, public-access kiosks, ATMs, check-out systems, machine control, and oil and gas exploration as well as mining applications.

On the down side of display integration, the military and government market, one of the previous "rocks" of this region, is no longer a sure thing. Although the work still exists – as long as there are soldiers they will need ruggedized displays, for example – government programs are being cut or at least re-assessed. Many programs are being delayed by years, development money is hard to come by, and project volumes have been greatly reduced. The across-the-board U.S. government budget cuts that went into place last March have affected some parts of the private sector profoundly. Companies ranging from janitorial services to aerospace and science researchers (including companies who make integrated displays) have been forced to reduce spending as a result of military and government cuts.[3] In the case of military display integrators, who have been busy updating mobile devices, in many instances replacing laptop models with tablet and smartphone configurations, money has already been spent on projects that are not going to be paid for any time soon.

South of Canada and the U.S., there is some new manufacturing action. In 2012, Mexico became the world's largest exporter of flat-screen TVs.[4] The work involved is actually final assembly, using parts from Asia. It is what is called a "box-build" business, which does not require a high level of technical expertise, but certainly represents a much-needed boost to the Mexican economy. The country became a prime assembly spot for U.S.-bound big-screen TVs after the North American Free Trade Agreement (NAFTA) passed almost 20 years ago, allowing goods produced in Mexico to enter the U.S. duty free. The cost of shipping big TVs from Mexico to the U.S. market is certainly less than it would be to ship them from Asia.

There is general consensus in the U.S. and Canada that plentiful manufacturing opportunities represent a sort of bygone Golden Age. In fact, manufacturing remains relatively strong in the U.S., but has changed in makeup. Much more of the factory floor work is done by robotic equipment, and the workers who maintain it often require specialized training beyond what they would receive on the factory floor.[5] The manufacturing jobs requiring large numbers of workers currently remain overseas. It is possible that some will return to North America because of tragedies like the factory collapse in Bangladesh last April, but that depends on the degree to which new concerns about working conditions translate to higher costs overseas.

Both display integration and final product assembly are the most likely manufacturing candidates to return to the region. Big screens are expensive to ship (hence the growth of the TV assembly business in Mexico). The need for specialized assembly and high degrees of customization argues for display integration done near the customer – the aforementioned market for displays in cars fits nicely into this model. Lastly, North American companies with unique intellectual property may find it easier to protect and implement their know-how closer to the source.

Display fabs, however, are unlikely to return to North America. Now that they, along with the requisite expertise (and highly needed capital) involved in starting and operating them, are in Asia, it makes sense to keep them there. "And the reason is the supply chain as much as anything else," says Semenza.

Starting Up, Setting Out

For companies with new display technology to roll out, it can be difficult to find investors in North America. "It's still tough to get funding here because venture-capital companies (VGs) are nervous about hardware," says Semenza, adding that software investments are more popular. Still, funding exists, especially from companies such as Microsoft and Amazon (which recently purchased Liquavista), and start-ups do happen. Sometimes companies even manufacture in North America. One example is E Ink, which began as a spin-off from MIT in 1997. E Ink has headquarters in Cambridge, Massachusetts, and is currently planning to relocate them to nearby Billerica, Massachusetts. In 2009, E Ink added a manufacturing plant in South Hadley, Massachusetts. (All ink and laminations are done in Massachusetts; cutting and final assembly are done in China.)

Companies that would make or sell products in the U.S. should know that regulations, taxes, and environmental requirements there vary greatly. "The rules are different from state to state, and even from town to town," says Sri Peruvemba, Chief Marketing Officer at Cambrios Technologies Corp. (and formerly of E Ink). "But it's a democracy – you express yourself!" Many companies have found that the safest way to be sure of complying with environmental and energy guidelines is to follow those of California, which has traditionally been the strictest (or most forward-thinking, depending on your point of view) state in terms of those kinds of regulations.

For display companies looking to deepen their involvement in North America, it's best to bear in mind that it's a region long on intellectual capital and consumer enthusiasm, but short on easy paths to success. Barriers abound, from monetary, regulatory, and even legacy considerations that make it difficult to raise capital for local manufacturing, to a somewhat fickle buying population that has become accustomed to receiving high-quality goods at margin-threatening prices. But if you can gain market share and consumer mindshare in North America, the visibility gained might well take your enterprise global, as companies such as Microsoft and Apple have demonstrated.

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Loctite® 3191, 3198, 3199 for Direct Bonding
Loctite® 3194 for Cover Lens Bonding

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