MOBILE DISPLAYS ISSUE

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SID
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The Future of Mobile Devices

DISPLAY INNOVATIONS THROUGH MEMS-BASED TECHNOLOGY

NEW PIXEL MEMORY CIRCUITS AND POLYMER-NETWORK LC MATERIALS

EVOLUTION OF MOBILE DEVICES

4G NETWORKS PROMISE WIDER AND FASTER BANDWIDTHS

HAPTIC INTERFACES TO ENHANCE USER EXPERIENCE

Plus
Journal of the SID November Contents

***COVER**: Mobile devices have been transformed by innovations in hardware and next-generation mobile networks. Requirements for displays have gone in the direction of larger and brighter displays capable of showing more information at higher quality. Also, there has been an increasing integration of touch technology into mobile devices. The manufacturers of mobile displays have met these needs by offering improvements in display performance, thickness, weight, and power consumption.*

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Next Month in
Information Display

Liquid-Crystal-Display Technology Issue
- Emerging LCDs Based on the Kerr Effect
- Innovative LCD Materials
- Adaptive Backlight Dimming for LCD Systems
- Trends in Large-Area LCDs
- The Success of Netbooks
- *Journal of the SID* December Contents

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Continuous Improvement Starts at Home

by Stephen Atwood

Similar to the mantra being chanted at nearly every commercial company I know, we at *Information Display* are always asking ourselves how we can do better and what lessons we can learn from our experiences so far. By doing this, we're following the well-known practice of "continuous improvement." In the publishing business, improvement opportunities come in many forms, some mundane and procedural, some artistic in nature and having to do with look and feel, and some in the form of the fundamental elements of the content we produce. Of course, in order to be effective at any continuous improvement, you need to know your customers and listen to them when they or the marketplace around them are trying to tell you something. The challenge is often not in just listening to your existing customers, but also in better understanding what your customers' customers are telling them. In this still-challenged economy, almost every activity is being constantly scrutinized for maximum efficiency and value to the next level of consumer in the chain. That's a fancy way of saying that everyone in every conceivable supply chain today is demanding more value for less cost and faster turnaround with less risk. At *ID*, we view our business as having three distinct groups of customers: the first and most important, as always, consists of our readers, including all the members of the Society for Information Display and many more in the industry who receive *ID* by qualifying subscription. A fairly new group of readers has recently joined us on-line through our Web site, www.informationdisplay.org, where we invite one and all to join and read frequent industry news updates as well as all the articles, columns, and features printed in the magazine.

Our second and equally important group of customers is represented by all the great businesses that support *ID* each month through their advertising and related support. Their products and services are prominently featured in each issue and we strive to give them the best value possible for their marketing dollars. We understand that they are under tremendous pressure in the current economy. In this vein, we are frequently looking at ways to improve our value to advertisers, recognizing that *ID* can play a valuable part in the process of connecting display companies to their target customers.

The third customer group includes the many Guest Editors and individual contributing authors who work tirelessly each month to create the great features we get to publish. These individuals offer their time and talent to help educate the rest of the industry. In most cases, they do so with the support and encouragement of their employers. Nonetheless, their efforts are almost always "extra-curricular" and therefore it is important for us to provide the best possible experience and a compelling value for those who want to write and be heard in the industry.

I've described these three groups so I can better explain why we are undertaking some changes to the format of *ID*, implementing what we believe will be improvements for all three of our customer groups and hopefully producing additional value for all those associated. Specifically, beginning with this October issue you will notice some new features and a slightly broader focus to our coverage of the display industry. Displays are, in fact, a segment of the larger electro-optical industry and display technology is used in or alongside practically every conceivable electronic system. In order for those in the broader community to optimize their products, they need to understand the full breadth of opportunities display components and technology

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industry news

Green Legislation for Display Manufacturers

by Jenny Donelan

Manufacturing companies taking a stronger environmental line these days do so because it's good for public relations, good for business, and good for the soul – and also because they are required to do so, if not now, in the near future. Many regulations, mostly from the European Union, are making it necessary for businesses to take a harder look at their supply chains. With some exceptions, companies in the United States have not had to do this to the extent that their overseas partners have "All the toughest legislation comes out of Europe – or California – these days," says Kimberly Allen, principal of Paňña Consulting. But as a practical matter, any company that wants to do business globally, and that includes most display companies, has to make sure that its products comply with EU rules. New legislation from other parts of the world – Asia, for example – is also in the works, and old legislation is constantly changing. RoHS, which went into effect July 2006, is currently being updated, as is REACH. These directives will only become more stringent.

Below is a short list of the environmental legislation most likely to affect display manufacturers. The accompanying Web addresses contain more information about specifics, deadlines, and exemptions.

- **RoHS** (Restriction of Hazardous Substances). The directive originated in the European Union and restricts the use of specific materials found in electrical and electronic products: lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls, and polybrominated diphenyl ethers. http://www.rohs.gov.uk/ Since RoHS covers every component of a product, manufacturers need to know who made which components and where each component was made. "Some little pushbutton on your phone might have been made in one country and gone through two or three different factories in other countries" before it ends up in a finished handset, notes Allen.
- **REACH** (Registration, Evaluation, Authorization, and Restriction of Chemical Substances) is an EU directive that came into force in 2007, but is being phased in over a period of years. Similar to RoHS, it requires manufacturers to know the origin and contents of their products. Unlike RoHS, it does not ban substances (although it calls for progressive substitution of the most dangerous ones) but asks that all listed materials, harmful or not, be cataloged in a database. "RoHS involves six substances," says Allen. "REACH deals with 10,000–20,000." Whoever is deemed responsible for the product, usually the OEM, she notes, will need to maintain the necessary database. Manufacturers will be expected to be in full compliance with REACH by 2011 or 2012, she estimates. http://ec.europa.eu/environment/chemicals/reach/reach_intro.htm
- **WEEE**, another piece of legislation from the EU, is the Waste Electrical and Electronic Equipment Act, in force since 2003. Unlike RoHS and REACH, "It's more about the end of life of a product," says Allen. WEEE was designed to promote collection schemes for the recycling of electronic equipment, although it also requires that heavy metals and certain other chemicals be phased out of products. The directive sets targets for collecting and recycling, and places the onus, for the most part, on manufacturers. Some companies, such as Dell, have been fairly proactive about this, offering free computer recycling to customers worldwide (see, www.dell.com/recycling). Certainly, end of life is a challenge for the entire industry. Even cell phones, which might seem, on account of their portability, to be easy for customers to recycle, represent a lot of potentially hazardous waste. According to Allen, only about 10–11% of cell phones in the U.S. are currently recycled. "The rest end up in desk drawers or in landfills," she says. http://ec.europa.eu/environment/waste/weee/index_en.htm
- **Electronic Waste Recycling Act.** This 2003 legislation out of California also has to do with end of life. Key elements of the ruling include a reduction in hazardous substances used in certain electronic products sold in the state, collection of an electronic waste-recycling fee at the point of sale (about \$8–\$25 per viewable screen, according to Allen), and distribution of recovery and recycling payments to qualified entities handling the cost of electronic waste collection and recycling. http://www.ciwmb.ca.gov/electronics/Act2003/
- **EuP** (Energy-Using Products) is yet another EU directive (finalized in 2005 but not yet enacted) and is aimed at encouraging environmentally friendly design before the supply chain even gets exercised. "It requires DfE (Design for Environment) to have occurred before you make the product," says Allen, who adds that it will involve some type of stamp that can be displayed by approved products. http://ec.europa.eu/enterprise/eco_design/index_en.htm

Environmental legislation has already changed the way business is done in many areas of display manufacturing, and it will continue to do so in greater and greater measure. Some of the challenges are daunting: cataloging all the substances under the REACH directive, for example, will take time and cause some pain. Allen believes, however, that the end result will be positive. Companies will have a better knowledge of their supply chain and closer relationships with suppliers. "I think it has the potential to harmonize the supply chain," she says.

A question on some people's minds – at least in the U.S. – is, "Do companies really have to comply yet?" The answer is, "In most cases, yes." Admittedly, enforcement and penalties are not standardized, and in some cases have been phased in over time. And there are exemptions, such as for medical equipment. But the processes of detection and enforcement are becoming more rather than less rigorous and legislative overhauls will provide for fewer exemptions as time goes on.

What actually happens if a company is discovered to be in violation of a directive depends on where the detection takes place. In the case of the EU directives, for example, it is up to individual countries to achieve results, and the EU does not dictate the methodology. Checking for compliance might mean requesting documents in one instance. It could mean physical checks with handheld XRF (X-ray fluorescence) analyzers in another, or both. Penalties vary as well. For non-compliance with WEEE/RoHS, examples include a fine of 300,000 Forints

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president's corner

Going Viral, Getting Passionate

by Paul Drzaic
President, Society for Information Display

I've been thinking a bit about what it takes to be noticed, to rise above all the news and advertisements that bombard everyone and to capture the public's imagination. Especially for people who design technologies and products for a living, getting our work noticed is one thing, but generating passion among our customers or peers is another. Going viral is an apt description of the latter phenomenon. Some bit of news starts small, but strikes a deep chord in those who see it. Like a true virus, it gets passed to others, leading to an exponential rate of infection. Sometimes the infection is cured, but in other cases it lingers, and people become deeply connected.

Some viral events are silly and fun. The "Banff squirrel" made headlines in August of this year, when a squirrel showed up in the foreground of a photograph of a couple taken at Banff National Park in Canada. Someone thought the resulting image was funny and edited the squirrel into other photographs. Next thing you knew, everyone was doing it, and images appeared on the Internet of the squirrel participating in the Apollo 11 moon landing, meeting with U.S. President Abraham Lincoln over 100 years ago, and joining in the recent diplomatic mission by Bill Clinton to North Korea. Almost as quickly, the event was over and the squirrel went back into its hole. It now is a piece of trivia preserved on the Internet (search on "Banff squirrel" to check it out for yourself).

The success of some electronic products has viral aspects to it. The most recent examples have come from Apple and from Amazon. Apple's iPhone, and a few years before that its iPod, turned entire industries upside down by creating surges in demand in product categories that were rather sleepy before. Amazon's Kindle created a buzz in electronic books as a category that never before existed. Both Apple and Amazon have developed a passionate base of customers that will likely return to them for future products time and again because these companies connected deeply with a perceived need and exceeded expectations.

What does this have to do with displays? Well, I'll note that getting people passionate about products tends to enhance the value of technologies associated with that product. Take touch screens – this technology has existed for years and was primarily something used for applications such as bank ATMs and industrial panels. At the SID Symposium, we would receive a few papers per year at most on these technologies. Since the iPhone introduction, though, touch has become one of the fastest growing areas in display technology development and deployment. Likewise, for many years, electronic-paper technology was primarily a solution desperately searching for a market-based problem to solve. Amazon has now solidified electronic paper as a viable display category and generated new enthusiasm for the field.

So what's the next viral product that will bring a new technology along with it? 3-D home theater? OLED portable tablets? Flexible displays in consumer packaging? Pay attention, as those that catch the virus early might very well reap some pretty important rewards. ■

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Enhancing Mobility through Display Innovation

As consumers become increasingly reliant on mobile devices with large displays and computer-like functionality, device designers need to address limitations in both power and visibility across all lighting environments. Micoelectromechanical systems (MEMS) technology is a promising solution.

by Jim Cathey

MOBILITY – whether in the form of a smartphone, a netbook, or an e-reader – has become an integral part of many consumers' professional and personal lives. And as the literal window to the mobile world, the display plays a central role in consumers' mobile experiences, shaping their interactions with content ranging from GPS to Web browsing. However, limited battery life and poor screen visibility in outdoor lighting conditions currently stand in the way of a truly mobile experience. Emerging reflective-display technologies have the power to disrupt the current order and take consumers' mobile lifestyles to the next level.

Modern Mobile Lifestyles

Today's mobile-device designers face unprecedented opportunities: handsets have evolved from primarily voice-driven devices to highly visual platforms for multimedia and new mobile categories such as netbooks and e-readers are quickly gaining momentum. The mobile industry is seeing a proliferation of new applications and functions that – whether essential or trivial – are being quickly absorbed into consumers' mobile lifestyles.

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The industry has also reached a critical juncture: in order for mobile innovation to continue along its current trajectory and satisfy consumer appetite, hardware technology must keep up with the spike in mobile functionality and consumers' increased usage. Today's mobile users face two key limitations in terms of the display: inadequate battery life and inconsistent screen visibility across varied lighting environments. (From a network point of view, bandwidth is also a problem; see "The Approach of 4G," also in this issue.) Consequently, consumers have had to adapt their behavior to accommodate power and readability limitations that dictate how, where, and when they can interact with their mobile devices.

Today's designers are consequently tasked with balancing the demand for feature-rich mobile products with device capabilities to support such functions. And given consumers' fixation with style – as evidenced by

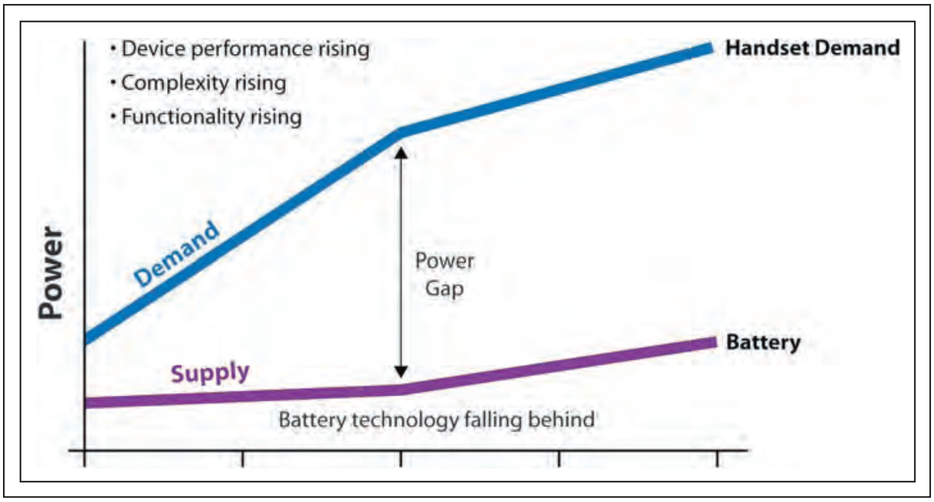

Fig. 1: It is well understood that as handset energy demands increase faster than battery longevity, the "power gap" between the two will widen.

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the popularity of Apple's iPhone – designers need to achieve this balance without compromising aesthetics or straying from small, sleek devices. Identifying solutions that address both power and visibility issues while enabling the appearance consumers demand is key to enhancing the functionality of the mobile products of today and tomorrow and surpassing consumers' expectations.

Demanding More from Displays

In the search for a hardware solution that addresses both power consumption and screen visibility, designers need look no further than the display. As the mobile phone has evolved, the display has taken on an increasingly vital role in the consumer's mobile experience as the literal window to the mobile world. Consequently, the spike in usage of sophisticated, multimedia-rich mobile functions has placed unprecedented demand on the display, which in the current marketplace has become the chief offender with respect to draining battery life and offering poor outdoor visibility. Consumers have adapted behaviors such as reducing usage of power-draining functions to lengthen battery life, relying on power cords and outlets to make it through the day, and shielding their devices and squinting in bright sunlight.

With today's dominant mobile-display technology – liquid-crystal-display (LCD) technology – these attempts to compensate are essential. While the LCD delivers a bright, sharp display experience in dimmer lighting conditions, the image quality deteriorates noticeably outdoors, particularly in direct sunlight. And because the technology relies on an energy-demanding backlight, the LCD is a significant consumer of a device's available power, especially when multimedia-rich applications are in use.

The Mobile-Device Power Gap

LCD technology is today's most ubiquitous display technology, and the LCD is one of the most energy-hungry of all typical mobile components. This is because the LCD polarizer limits the amount of light reflected or transmitted, so that at least 50% of available light is discarded. Due to additional layers such as color filters, the display transmits only 6% of the ambient light. Consequently, a significant amount of backlight power is required to achieve the bright visual experience today's consumers have become accustomed to.

The power drain brought about by the LCD has only recently become a significant pain point for consumers. Before the incorporation of multimedia-rich functions into our mobile lifestyles, handset performance was gauged in large part by reception quality and talk time. In many ways, the handset has transformed from a device that consumers talk into to one that they experience visually through functions such as video, Web browsing, gaming, and GPS. The power gap between consumer demand for mobile functions and handset capabilities continues to widen (see Fig. 1) as usage of these functions outpaces advances in small-form/high-power-generating battery technologies such as lithium ion cells. Consequently, the LCD's power needs force consumers to limit their displays' "on" time or remain tied to power cords and outlets.

This is not meant to discount the progress being made in the battery sector, but rather to underscore the importance of supplementing battery technology advancements with other more immediate energy solutions that address the widening power gap. The industry needs to focus on reducing energy consumption on the demand side through hardware solutions that enable continued innovation without forcing consumers to limit their mobile behavior. And, of course, it should be acknowledged that the companies that produce LCDs are also looking into ways of becoming more energy efficient. For an early look at a low-power reflective LCD technology for mobile phones, see, "Making a Mobile Display Using Polarizer-Free Reflective LCDs and Ultra-Low-power Driving Technology," also in this issue.

Metrics for Real-World Visibility

In addition to adapting behavior around power cords and outlets, mobile users have grown used to shielding their devices or searching for dark corners of shade when outdoors. As mobile devices – handsets, MP3s, e-readers, and products yet to be invented – become increasingly integral to consumers' professional and personal lives, viewability across a broad range of lighting environments will match battery lifetime as a pivotal concern.

Current metrics are divorced from what the human eye is capable of perceiving; they are based on contrast ratio, color gamut, and bit depth, which, while helpful, do not provide a real-world indication of a display's performance. Contrast ratio and color gamut are both gauged in testing labs in dark-room conditions to generate consistent and favorable results; however, both of these measurements change significantly as the display operates in a more typical real-world environment. Furthermore, bit depth is technically not a visual characteristic of the display, but rather a specification of the device's electric circuitry. Consumers in the market for a mobile device are without an accurate description of how the display will perform outside of a dark room, whether in the office, car, or outdoors. The International Committee for Display Metrology (ICDM – www.sid-icdm.org) is currently working on some very precise methods for measurement of display contrast and color under ambient conditions, with the aim of making them easy to implement and very repeatable.

Mobile Color Depth (MCD) is a set of metrics developed by Qualcomm MEMS Technologies (QMT) that is based on display performance in real-world conditions using the vision-science concept of a just-noticeable difference (JND), a measurement of what viewers can and cannot discriminate in an image. MCD bridges the disparity between today's display specifications (addressable levels) and actual visual experience (perceptible levels) by describing the number of perceived colors generated by a display in a specific viewing environment. A detailed overview of MCD methodology can be found at http://www.mirasoldisplays.com/ mcd/.

MCD has been designed as a resource for consumers at the point of sale, enabling them to make purchasing decisions based on metrics that convey how the display will perform in their day-to-day lives, rather than on numbers measured by technicians in dark rooms. It also serves as a tool for the entire mobile-device value chain, helping various players to more accurately select their display experience. When designers take into account environments in which consumers will interact with the display, product managers will be able to select features and applications accordingly and carriers will anticipate greater available revenue time (ART) from devices that can be fully utilized irrespective of lighting conditions.

Emerging Reflective Displays

Display technologies of the future need to address both the widening power gap and consumers' need to interact with their devices in a variety of lighting environments.

ABI Research underscored the demand for improved display performance in a report released in January, 2009: "Emerging Displays in Mobile Handsets." The report explains that the LCD "is still king" in the mobile-display landscape, but then identifies three emerging challengers to its throne. In addition to organic light-emitting diodes (OLEDs), ABI Research names two reflective-display technologies as the leading contenders: e-ink, the "electronic paper" display used in Amazon's Kindle, and the mirasol display from QMT. While LCD technology has improved significantly since its inception, ABI Research explains that these new reflective displays excel where LCDs falls short; namely, power consumption and visibility in bright lighting conditions.[1]

Reflective-display technologies have been slow to find success in commercial devices but are now gaining traction thanks to their significant impact on both power consumption and screen viewability. The reflective e-ink display has been incorporated in numerous e-readers in addition to Amazon's Kindle. Due to its reflective nature, the e-ink display draws minimal power and can be designed to mimic ordinary ink on paper for maximum readability, making it well-suited for e-reader functions.

An electrophoretic display, such as that used by E Ink Corp., is capable of holding a stable image without constant need of refresh and reflects light rather than emitting it. These attributes contribute to enhanced energy efficiency and visibility in direct sunlight.[2] Current generations of electrophoretic displays are suitable for imagery that changes relatively slowly and infrequently, such as eBook readers, rather than full-motion video. So, while electrophoretic technology is indeed an exciting new technology, its application to mobile devices is currently somewhat limited.

MEMS Displays

Also in the reflective category as noted by ABI Research is QMT's Interferometric Modulation (IMOD) based technology: the mirasol display. Microelectromechanical systems (MEMS) technology has existed for about the last 30 years and has more recently formed the basis for mirasol technology. QMT engineers developed the mirasol display by studying and mimicking processes and structures in nature. The most brilliant colors that occur naturally are brought about by optical interference within minute biological structures. Such interference results in "iridescent" colors that can represent any portion of the rainbow and change based on viewing angle. There are many examples of iridescent color in nature, including mother of pearl, peacock feathers, the scales of some beetles, and the wings of a butterfly.

The wings of certain butterflies have tiny scales and ridges that reflect light in such a way that only certain colors are perceptible to the eye. This is essentially the same principle employed in mirasol displays: the butterfly's wing structure, with its multitude of layers and imperfect ridges, were what the early designs of the IMOD-based product mimicked. However, engineers then discovered that by precisely controlling the thickness of the reflective layers in the mirasol display, only two layers were necessary in order to create iridescent color in the same manner as the multiple layers of a butterfly's wings.

The mirasol display uses a combination of MEMS mirrors and thin-film fabrication technologies common in the flat-panel and semiconductor industries to create a spectrum of colors by reflecting light so that specific wavelengths interfere with each other to select the emitted colors. When ambient light hits the structure, the light is reflected both from a thin-film stack and off the reflective MEMS mirrors. Depending on the height of the optical cavity between these two layers, light of certain wavelengths reflecting off the mirrors will be out of phase with the light reflecting off the thin-film structure and other wavelengths will be in phase. Based on the phase difference, some wavelengths will constructively interfere, while others will destructively interfere. Figure 2 shows the layers involved in a mirasol display.

This design not only produces vibrant colors, but also inherently has low power requirements and sunlight viewability. The display's bistable nature allows for near-zero power usage in situations where the display image is unchanged, resulting in considerable power savings compared to displays that continually refresh or require a constant charge to each pixel. The power currently used for backlights can be reallocated to support functions and applications, reducing total device power consumption by 40% when compared to conventional LCDs.[3] Furthermore, the mirasol display has a rapid refresh rate, making it suited for multimedia-rich applications such as video. Power savings combined with video-rate capabilities enable consumers to enjoy multimedia-rich functions without concern for battery life, and carriers in turn benefit from an increase in ART. Contrast and readability also remain across a broad range of lighting conditions, including direct sunlight, with no need for a backlight.

Commercializing an Emerging Technology

Given the above performance benefits, why isn't the mirasol display ubiquitous in today's mobile products? It's important to keep in mind that this is an emerging technology – in its relatively short lifespan, the mirasol display has already seen significant traction with three products in the marketplace and the launch of a dedicated color-mirasol fabrication plant.

The aforementioned ABI Research report identifies two primary hurdles facing the mirasol display and any other emerging display technology: volume and cost. LCD technology is a mature technology with manu-

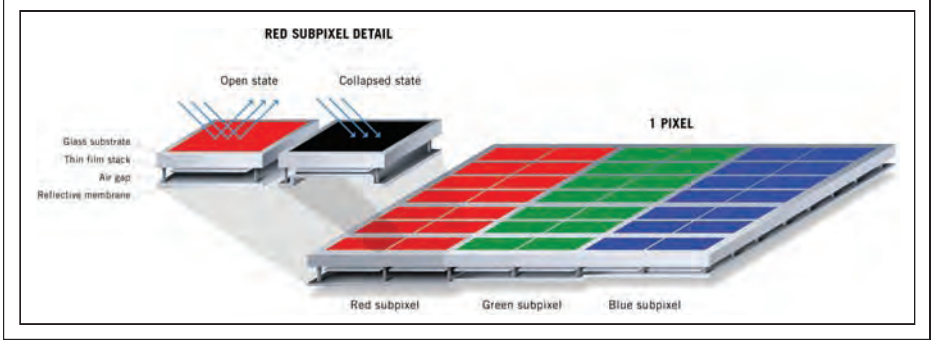

Fig. 2: *The color of each IMOD substrate is determined by the size of the gap between the layers.*

facturing infrastructure in place, so its comparatively low cost gives it an advantage over contending technologies.[1] The ability to produce in volume is the first step toward lowering cost, and consequently both e-ink and mirasol displays have made significant strides towards this end. In June 2009, Prime View International (PVI) signed an agreement to acquire E Ink Corp. for $215 million, a deal which is expected to close in the fourth quarter of 2009.[4] The acquisition should shore up the manufacturing capabilities for e-ink technology.

QMT also reached a major milestone in June 2009: the opening of a dedicated mirasol-display fabrication plant in the Longtan Science Park in Taoyuan, Taiwan. The facility represents a strategic collaboration with Cheng Uei Precision Industry Co. Ltd., (Foxlink), a leading manufacturer of communications devices, computers, and consumer electronics. QMT will utilize its process-engineering expertise from dedicated teams in Taiwan and the Qualcomm MEMS Research and Innovation Center (MRIC) laboratory in San Jose, California, and Foxlink will play an integral role in the operation of the mirasol fabrication facility. The dedicated fabrication plant will enable greater volume and faster time to market.

Mobile Devices of the Future

The mobile landscape is shifting – consumers are becoming increasingly reliant on mobile devices for their professional and personal lives, and in order to maximize how, where, and when they can interact with these products, designers will need to address both the power gap and the need for functionality across all lighting environments. Future display technologies should free consumers from power cords and allow them to quite literally emerge from the shadows and experience mobility on their terms. The mirasol display is an emerging technology with significant milestones ahead, but as it continues to mature, it will open the door for designers to create products and markets that do not yet exist due to power and visibility limitations.

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Making a Mobile Display Using Polarizer-Free Reflective LCDs and Ultra-Low-Power Driving Technology

Through refinement of materials and fabrication conditions, a reflective display with reduced flicker and image sticking at low frame rates was produced. The display consumes very little power and works in a wide range of temperatures, making it a potential platform for future mobile devices.

by Kiyoshi Minoura, Yasushi Asaoka, Eiji Satoh, Kazuhiro Deguchi, Takashi Satoh, Ichiro Ihara, Sayuri Fujiwara, Akio Miyata, Yasuhisa Itoh, Seijiro Gyoten, Noboru Matsuda, and Yasushi Kubota

ELECTRONIC DISPLAYS have become commonplace in our daily lives, and low power consumption is more important than ever before. The power consumption of conventional electronic displays is still high enough to limit the amount that it uses or the environments in which it operates effectively. Technologies such as reflective displays and low-frame-rate driving, as well as the ability to "memorize" images, are effective in producing low-power-consumption displays. Imagery can be memorized (held in memory while drawing very little power until the image changes) using electrophoretic[1] or cholesteric liquid-crystal technology,[2] but displays based on these technologies tend to require relatively high driving voltages and produce slow responses.

A combination of a reflective-type liquid-crystal display (RLCD)[3] and a drive scheme such as a low-frame-rate drive[4] or a pixel-memory circuit[5,6] should be a promising candidate for mobile devices. Because the power consumption of an LCD module generally depends on the driving frequency, the lower the frame rate, the less power the module consumes. And the pixel-memory-circuit technology enables the module to "memorize" images in the pixels with the data driver suspended.

An RLCD using polymer-dispersed liquid crystals (PDLC)[7] can control the transmission or scattering of incoming light rays without the use of polarizers. Its features of note include high light-utilization efficiency due to a polarizer-free system and a low level of dependence on viewing angle. Although a PDLC usually requires a high driving voltage, a polymer-network LC (PNLC) containing a high LC content ranging from 70 to 90 wt.%, which is higher than that for a conventional PDLC, shows relatively lower driving voltage. Therefore, a PNLC is one solution toward realizing an energy-savings paper-like display. In the meantime, a PNLC holds a couple of challenges for TFT drives. These include slow response and a low voltage-holding ratio. However, recent progress made in PNLC materials has enabled TFT driving of a PNLC by improving the above properties.[8]

Objective

Our objective was to develop an ultra-low-power-consumption RLCD with excellent viewing properties by using a 1-bit pixel-memory technology and a PNLC. This resulting display is composed of a PNLC layer formed between the transparent electrode and mirror-reflective pixel electrodes and 1-bit pixel-memory circuits embedded in the pixel area under the reflective-mirror electrodes. This PNLC mainly utilizes front scattering and a mirror reflection for the displayed imagery; therefore, a 3-μm thickness is

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enough to achieve high reflectance (50%). And all the circuits of the display are fabricated by low-temperature poly-Si (LTPS).

Pixel-Memory Technology

The system block diagram of our newly developed pixel-memory display is shown in Fig. 1.

The interface of this display is very simple because only five input lines are necessary for operation, including power supplies. A timing generator with a three-line serial-interface circuit, common electrode driver, polar-inversion circuit, and pixel-memory circuits embedded in each pixel are integrated with the scan driver and data driver monolithically on the glass substrate. When displaying still imagery, the image data is stored in the pixel memories, so that it requires no input for refreshing the image data – only the power supply. Moreover, because all the systems are composed of CMOS digital circuits, only 5 V is necessary for operation. Therefore, this display can achieve ultra-low power consumption.

PNLC Technology

The PNLC layer, with a micro-separated structure of liquid crystals and polymer networks, is manufactured by irradiating a mixture of monomers, liquid crystals, and a photo-initiator under UV light. The morphology of the polymer network is shown in the cross-sectional scanning-electron-microscope image shown in Fig. 2.

The droplets are not isolated from each other, but have a sponge-like appearance, and the diameter of a droplet is approximately 1–2 µm. The morphology of the polymer network is critical in determining the electro-optic properties of the PNLC. This morphology is controlled by the kinetics of photo-polymerization. It depends on the concentration of the photo-initiator, the UV intensity, the UV curing temperature, and the surface treatment of the substrates.

The system has no polarizers, so the images are displayed by switching the PNLC layer between the scattering states and the transparent states. In the absence of voltage, the layer scatters due to the variation in the symmetry axis of the LC director in the droplets, which leads to a mismatch in the refractive indices in the different droplets; application of sufficient voltage causes all the LC directors to align vertically and the refractive indices to match in the different droplets, removing the scattering. The scattering PNLC breaks the specular reflection. The observer sees light and recognizes the images as bright (white) states [Fig. 3(a)] at all viewing angles. The transparent PNLC enables mirror reflection. Other than in the specular direction, the observer sees no light and recognizes the images as dark (black) states [Fig. 3(b)].

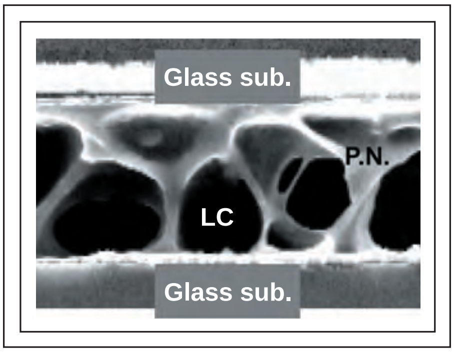

Fig. 2: *This cross-sectional scanning-electron-microscope image shows the polymer-network morphology of the PNLC.*

The PNLC normally exhibits a white state. So, in the white state, 0 V is applied to the PNLC, and in the black state, certain specific voltages are applied to the PNLC. Zero volts or another voltage is kept constant and applied to the pixel electrodes by utilizing the data stored in pixel memory. This drive scheme can operate at a low frame rate without problems, due to a less-than-100% voltage-holding ratio. Low-frame-rate operation using pixel memories could reduce the power consumption drastically, due to the low driving frequency of the data driver.

Power Consumption

Generally, the power consumption of an LCD is related to the driving frequency and the dis-

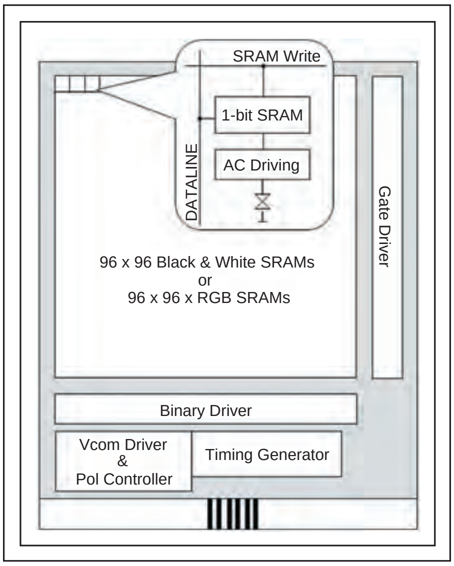

Fig. 1: *A system block diagram for the 1.35-in. prototype display is shown with both black-and-white and RGB SRAMs.*

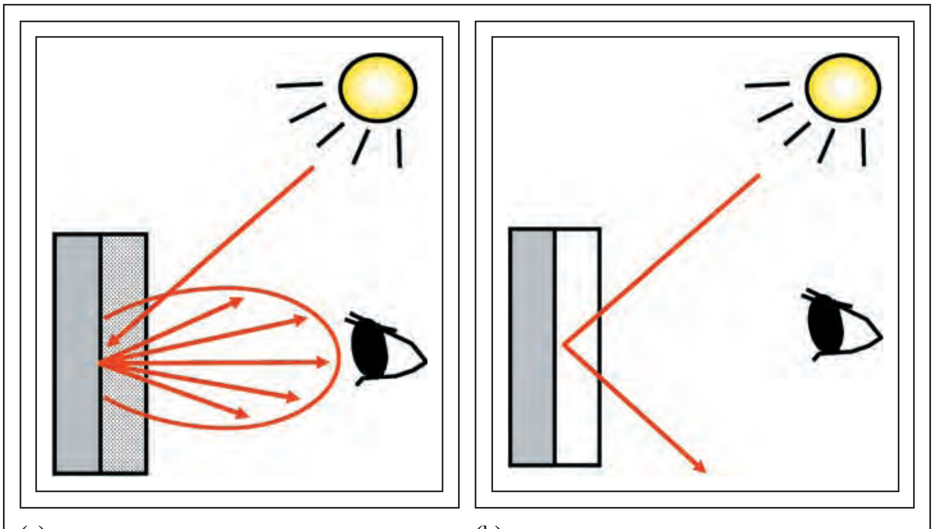

Fig. 3: *These illustrations show the principle of operation for the prototype. On the left (a) is the bright state. On the right (b) is the dark state.*

played image. The frame-rate dependence on driving power consumption for a 1.35-in. prototype display is shown in Fig. 4.

The power consumption drastically decreases with frame rate. The power consumption when displaying a clock pattern at 1 Hz is 10 µW for the monochrome panel and 25 µmW for the color panel. The power consumption when displaying a black pattern over the entire area at 1 Hz is 15 µW for the monochrome panel and 30 µW for the color panel. These ultra-low-power-consumption panels are realized by a well-controlled process technology that can reduce the leakage current of the TFTs. Each pixel in the color panel has RGB subpixels and a color filter. The power consumption of the panel is related to the number of pixels; hence, the power consumption of the color panel is larger than that of the monochrome panel.

Flicker and Image Sticking

In general, the human eyes are very sensitive to any flicker having a frequency below 60 Hz, but are especially sensitive to frequencies below 30 Hz. Therefore, the most important issue in achieving low-frequency driving below 30 Hz is to decrease the flicker. Image sticking is another big problem in low-frequency driving, due to the movement of impurity ions in the liquid crystal. In order to achieve an ultra-low-power-consumption PNLC display, a reduction in flicker and the inhibition of image sticking are absolutely imperative.

In this system, problems due to the less-than-100% voltage-holding ratio at low-frame-rate driving do not occur. However, when the frame rate is low to the extent of 1 Hz, impurity ions move easily and often form in the electric double layer. The electric double layer produces a reduced applied voltage to the PNLC and becomes a cause of flicker and/or image sticking due to the suppressed relaxation of liquid crystals, with each switching from the dark state (voltage on) to the bright state (voltage off). This flicker and image sticking can be observed in our system using regular PNLC materials. The blue line in Fig. 5 shows the resulting flicker and the image sticking.

The 30/0 reflectance, which is detected in the panel normal direction under parallel light incidence from a 30° polar angle, was measured by using an LCD5200 from Otsuka Electronics. The reflectance at the dark state, during a time period (x-axis) of 1–21 sec, changes periodically and produces a rectangular waveform. This reflectance oscillation is recognized as flicker. The reflectance gradually increases when switching from dark to bright, after a time period (x-axis) of 21 sec. This slow response of the reflectance is recognized as image sticking.

To reduce the flicker and to inhibit image sticking, the PNLC needs to saturate sufficiently at the driving voltage, and the impurities in the PNLC need to be reduced as much as possible. The electro-optic properties of a PNLC are determined not only by its LC properties, such as impurity concentration and saturation voltage, but by the morphology of the polymer network controlled by the kinetics of photo-polymerization.

By modifying the monomer and LC in the PNLC, we decreased the impurity concentration and the saturation voltage without a reduction in reflectance. The level of flicker and the relaxation time of the image sticking also decreased by reducing the amount of the photo-initiator in the PNLC (Table 1).

Here, the flicker value is defined as the value of the standard deviation of the 30/0 reflectance for the dark state. Relaxation time is defined as the time required for the 30/0 reflectance to change from 0% to 97% when the reflectance of the dark state and bright state is set to be 0% and 100%, respectively. This result indicates that the photo-initiator acts as an impurity in the PNLC even after the UV curing. But reducing the photo-initiator in the material caused a reduction in the reflectance and a weak reaction of the polymer networks in PNLC. Therefore, the preparation of the material is very important, as is the need for a sophisticated process for the PNLC, especially when operating at a low frame rate.

The electro-optic properties of a PNLC are also determined by the UV cure temperature and the UV intensity that strongly relate to the kinetics of photo-polymerization. The reflectance decreased with a reduction in UV cure temperature and UV intensity. The reflectance strongly depends on the diameter of the droplet size in the PNLC layer; the reflectance decreases with an increase in droplet size. Low UV cure temperature and low UV intensity bring about slow photo-polymerization-induced phase separation (PIPS). The slow PIPS forms large LC

Table 1: Influences of photo-initiator concentration on flicker and relaxation time. The samples were cured under the same conditions.

Initiator Concentration	Low	Middle	High
Flicker Value (%)	1.3	15.7	20.7
Relaxation Time (sec)	0.09	0.18	6.26

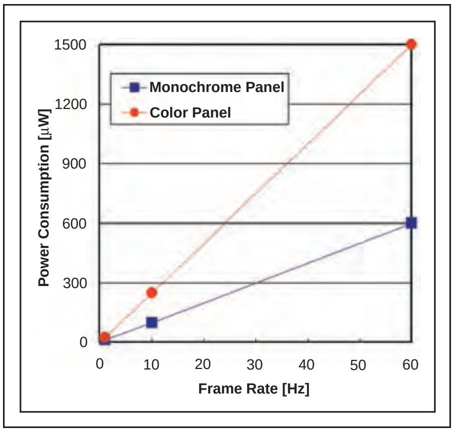

Fig. 4: Shown is the frame-rate dependence of power consumption for the 1.35-in. prototype display.

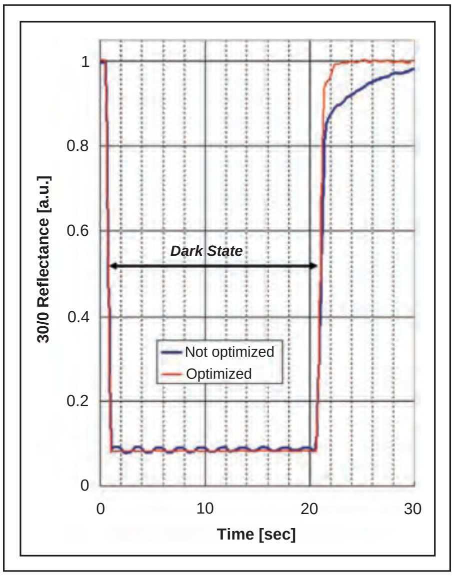

Fig. 5: This diagram shows the optical response of the 1.35-in. prototype display operating at 1 Hz, including flicker and image sticking (blue line).

droplets due to the long diffusion length of the monomer in the LC and results in low reflectance. In contrast, a high UV cure temperature and high UV intensity form small droplets due to the fast PIPS. The PNLC with small droplets also indicates a high saturation voltage owing to the increase of the surface anchoring effects between the LC and the polymer-network surface. Moreover, both high reflectance and low saturation voltage are achieved only at the mid-temperature range, which is a T_{nm} (the T_{ni} before the UV cure) of +3ºC and a T_{nm} of +10ºC in our material. The PNLC cured at this temperature range showed no flicker. In the meantime, the flicker value decreased with increasing UV intensity (Fig. 6).

On visual inspection, the flicker is invisible, with less than 0.5% of the flicker value. The PNLC without flicker is achieved by using a high UV intensity. The reduction in flicker by using a high UV intensity is probably due to the increase of polymer walls with a decrease in droplet size, which acts as a barrier against the movement of impurity ions and/or reduces the localization of impurity ions.

Consequently, we have succeeded in eliminating flicker and image sticking for low-frame-rate driving by modifying the material and optimizing the fabrication conditions of the PNLC layer, shown as the red line in Fig. 5.

Performance

The display images operating at a frame rate of 1 Hz are shown in Fig. 7.

The integrated reflectance value d/8 (which is detected at a polar angle of 8° under diffused light) of the monochrome display and the color display are over 50% and 20%, respectively. The d/8 reflectances were measured by using a CM2002 (Konica Minolta Sensing). Standard white (MgO plate) was used as the reference of 100% reflectance. Their contrast ratios are 10:1 and 5:1, respectively. These displays did not show any defects such as flicker or image sticking after low-frame-rate operation (1 Hz) at high temperature (70ºC) and low temperature (-20ºC) over 500 hours. Moreover, the defects were not generated after the storage test at 80ºC, at -30ºC, and under sunlight for over 500 hours. These environmental tolerances are almost equal to those of current conventional LCDs for mobile applications.

The specifications of these developed displays are compared with those of commercially available for typical displays in Table 2.

The integrated reflectance of the display is twice as high as that of a conventional RLCD

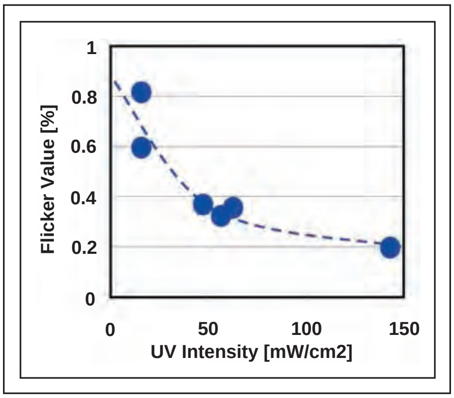

Fig. 6: UV cure intensity affects flicker value. Each sample received an even dose of UV.

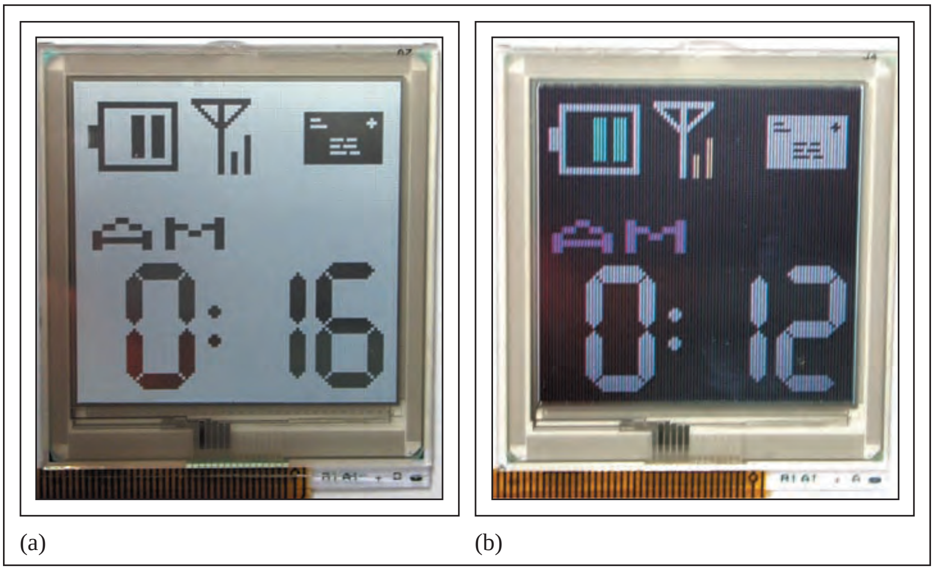

Fig. 7: On the left (a) is an example of a monochrome version of the 1.35-in. prototype. On the right (b) is the color version.

Table 2: Specifications of three types of displays. The conventional RLCD is a single-polarizer TN display.

	Novel RLCD		Conventional RLCD	Electrophoretic
Display Mode	**(Monochrome)**	**(Color)**	**(Color)**	**(Monochrome)**
Number of pixel	96 × 96	(96 × 3) × 96	(96 × 3) × 96	96 × 96
Integrated reflectance	50%	20%	11%	40%
Chromaticity (x, y)	(0.310, 0.333)	(0.310, 0.335)	(0.308, 0.341)	(0.305, 0.326)
Contrast ratio	10:1	5:1	15:1	7:1
Driving voltage	5 V	5 V	<5 V	15 V
Power consumption	10 μW (1 Hz)	25 μW (1 Hz)	2 mW	30 μW (1/15 Hz)
Operating temperature range	–20 ~ 70°C	–20 ~ 70°C	–20 ~ 70°C	0 ~ 50°C
Storage temperature range	–30 ~ 80°C	–30 ~ 80°C	–30 ~ 80°C	–25 ~ 70°C
Response time	100 msec	100 msec	50 msec	260 msec

with a polarizer and 25% higher than that for an electrophoretic display. In the case of common usage or an adequate switching frequency, the power consumption of our display is reduced to the level of around 1/60 of that of a conventional RLCD with a polarizer, and to the level of around 1/3 of that of an electrophoretic display, even though the power consumption depends on image contents.[9] Our display has other merits, including moving-image display capability and a wide-operating-temperature limit, whereas an electrophoretic display has difficulty displaying moving-images and an upper operating temperature limit of 50°C.

This reflective display, which has been created by the combination of pixel memory circuits and a new PNLC material has many features that are desirable in mobile devices: good visibility, low power consumption, and the ability to display moving imagery and to adapt to various usage environments. We have also reduced the level of flicker and image sticking at low frame rates by refining the materials and the fabrication conditions.

Acknowledgments

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DISPLAY WEEK SID

Tactile-Feedback Solutions for an Enhanced User Experience

Tactile feedback has been shown to greatly improve the touch-screen user experience, and the variety of actuation technologies available makes it possible in virtually any electronic device.

by Michael Levin and Alfred Woo

THE PROLIFERATION of touch-screen interfaces in consumer-electronics devices such as mobile phones is irrefutable, and it is easy to identify key attributes that make touch screens a compelling user-interface (UI) mechanism. Improved industrial design and mechanical durability, optimization of UI real estate, and the capability of leveraging a rich input-gesture vocabulary are a few that come to mind. However, the loss of tactile or *haptic* feedback, which users expect from conventional mechanical-input mechanisms, creates problems including higher error rates and user frustration. The solution is to add tactile feedback to the touch-screen interface to secure the best features of both touch screens and conventional controls. In fact, many device manufacturers have already done this; touch-screen mobile phones, cameras, and media players from companies such as Samsung, LG, Nokia, and RIM feature touch feedback to enhance the user experience. Haptic feedback systems have also been deployed in many non-consumer markets, including aerospace, automotive, casino gaming, medical, military, and industrial equipment. Other applications of haptics range from joysticks, steering wheels, and control knobs to touch pads, touch-sensitive switches, and keyboards.

Both quantitative task performance and qualitative user satisfaction have been shown to be significantly improved when haptic feedback is provided to the user. There have been many academic studies that confirm that tactile feedback bridges the usability gap between touch screens and mechanical controls. One of the most recent studies[1] concluded that the incidence of errors in touch-screen text entry was drastically reduced when tactile feedback was introduced. Moreover, subjects expressed a much lower frustration level with the enhanced interface and perceived text-entry tasks to require less mental and physical effort.

Research by Motorola[2] evaluated user preference for tactile and audio feedback on a mobile phone. Users were asked to compare audio-only feedback against synchronized audio and haptic feedback. More than 80% of the test subjects preferred the phone with both audio and haptic feedback over audio alone. The results also suggested that the haptic component enhanced the perception of audio quality.

In addition to augmenting the touch-screen interaction experience, haptics can also add a sense of touch to gaming for a more immersive experience, provide a rich non-audio channel for communicating alerts, and enhance the media consumption experience by adding a virtual subwoofer. The most satisfying UI feedback is multimodal, combining audio, visual, and tactile cues. In situations where audio or visual feedback is inadequate, such as distractive environments or in the case of vision- or hearing-impaired users, the tactile sense may be the primary mode of interaction.

Touch feedback has become a high-demand feature in touch-screen devices, and haptic actuation technologies are rapidly evolving as a result. The technology options can be confusing, but, in the end, the intended haptics usages and form-factor constraints largely determine the optimal actuation technology for the application. In the following sections, we outline the different actuation technologies and discuss the related hardware implementations.

Inertial Actuation

Inertial actuation is the most common and proven haptic actuation method. Virtually every mobile phone incorporates inertial haptic actuation; the vibrational alert is an example of simple tactile feedback using inertial actuators. What separates the typical vibrational alert from high-fidelity tactile feedback is the manner in which the actuators are driven.

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Inertial actuators in mobile phones are typically one of two types: a rotational motor with an off-center mass [eccentric rotating-mass (ERM) actuator] or a spring-mass system that vibrates in a linear motion [linear resonant actuator (LRA)] (Fig. 1). ERM actuators are available from a wide range of vendors, including Sanyo, Mabuchi, Johnson Electric, and others. LRAs are a more specialized component, and the majority of the LRA actuators in use today are manufactured by Samsung Electro-Mechanics Co. (SEMCO).

Even when used as a simple vibration motor, the two types of actuators are driven differently. The ERM is typically a DC motor and is driven with a simple DC on–off signal. The LRA, however, is driven at its resonance, so the input signal will be sinusoidal at the nominal resonant frequency of the spring-mass system, typically about 175 Hz, which is close to the 200–300-Hz peak-frequency sensitivity of the Pacinian corpuscle cells.[3] Pacinian corpuscles are nerve endings in the skin that respond to deep pressure and high-frequency vibration.

Creating high-fidelity haptics with inertial actuators is a matter of modulating the input waveforms to produce the desired mechanical response in the actuator. The dynamic response of ERMs can be drastically improved by using complex waveforms that may include momentarily overdriving the actuator to minimize rise time and actively braking to minimize spin-down time. A wide range of haptic effects can be created by using techniques that modulate waveshape, frequency, duration, and amplitude. However, to achieve the most compelling results, the waveforms must be tuned for the response characteristics of the specific actuator and integrated system. This step is particularly exacting and critical when trying to replicate the sharp feel of conventional mechanical snap domes or tact switches, which need to be very short and precise – the complete effect may last only 20 msec and the ERM shaft may rotate less than one full revolution. This precise control of actuator response distinguishes Immersion Corp.'s rich haptic feedback from the generic buzz of ordinary mobile-phone vibrational alerts.

Mechanically, the inertial motor is typically mounted to the device housing, and the inertial forces produced when the actuator is energized vibrate the entire device. This implementation is appropriate for small hand-held devices, such as mobile phones. However, it is also possible to incorporate inertial actuation into "fixed" or larger devices where only the touch screen is actuated. This requires a frame or holder that couples the actuator to the touch screen and some mechanical compliance in the system, typically a foam gasket, which allows the touch screen to vibrate independently of the housing. Immersion Corp. provides tools and services that support a range of inertial actuators for both handheld and fixed device applications.

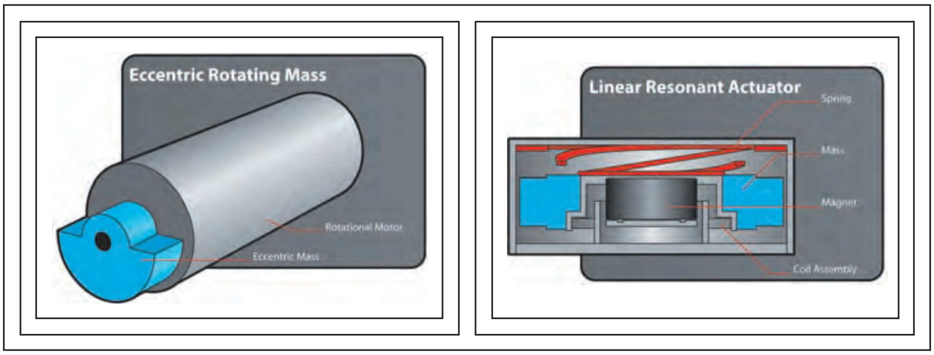

Fig. 1: *Shown above are typical rotational and linear actuators used to create haptic feedback in mobile phones.*

The impact of the haptic system on battery life is largely dependent on the usage model for touch feedback. If the primary usage is to augment touch-screen interactions with tactile clicks and other short-duration effects, the power draw of the haptics is fairly small and may impact overall battery life by only a few percentage points. However, if long-duration effects are used for alerts or gaming enhancement, this impact will become more significant. Inertial actuators, in particular, can draw in excess of 100 mA of current during transients, but this is usually offset by the very short duty cycle.

Inertial actuation is well-suited to handheld devices in which vibrating the entire device is desirable, and for larger or fixed devices if the requisite additional mechanical components can be accommodated. It is a proven technology that can be usually implemented with off-the-shelf electromechanical components.

Piezoelectric Actuation

While inertial actuation has been commonplace for as long as mobile phones have existed, there is currently a technology trend toward piezoelectric actuation of touch-screen haptics. Piezoelectric actuation offers several potential benefits: thinner form factor, faster response time, and high bandwidth. It also holds the promise of higher-fidelity haptics, a larger "vocabulary" of haptics effects, and the ability to integrate touch feedback into more demanding form factors – thinner devices with relatively large screens. However, there are also challenges associated with designing and integrating products with piezoelectric actuators.

Piezoelectric actuators are typically ceramic materials that deform when a voltage is applied. They are manufactured in a variety of shapes, but the types most commonly used for touch feedback are beams and disks. Piezoelectric elements have long been used as speaker transducers and sensors, but the use of piezoelctric elements for haptics actuation is still new. Major suppliers of piezoelectric transducers include Hokuriku, Kyocera, Murata, NEC-Tokin, and TDK.

Regardless of the shape, the behavior of the piezoelectric element is similar – voltage applied across the device results in deformation. In a beam, the deformation is in the form of bending. In a disk, the actuator flexes to bow up or down in the center (Fig. 2). When mounted appropriately, either behind or at the perimeter of a touch screen or liquid-crystal display (LCD), this deformation causes displacement of the touch surface as it is pushed away from a fixed surface.

The choice of beam *vs.* disk is largely a mechanical-packaging consideration. The thickness of the piezoelectric elements is typically between 0.5 and 3 mm, and the footprint will vary depending on the size of the touch screen and the haptic performance required. The disk is best utilized behind the LCD because its opacity and relatively large footprint do not

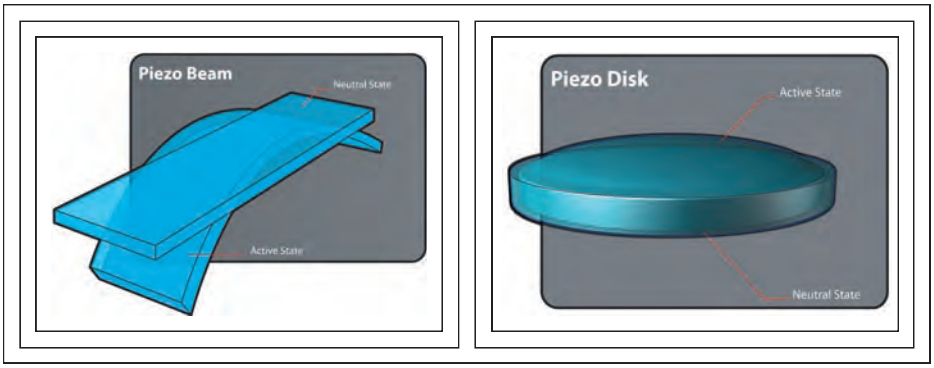

Fig. 2: *Piezoelectric beams and disks flex when energized.*

lend itself to integration above or alongside the viewable touch area. Beams can be used in either location, but minimizing sprung mass is important, so locating the piezoelectric beams outboard of the viewable area enables decoupling of the LCD from the sprung mass, improving performance considerably.

It is important to note that, unlike inertial actuation, piezoelectric-actuation systems can be designed to create haptic effects by either bending the touch screen or pushing the touch surface against another surface, resulting in translational motion. As a result, piezoelectric actuation is particularly well-suited for applications in which only motion of the touch screen is desired and not vibration of the entire device. Provided that the ratio of the unsprung mass to the sprung mass (*e.g.*, fixed portion of the device to the actuated portion of the device) is sufficiently high, adequate mechanical isolation between the two elements can be achieved to yield an experience that approximates a “touch-screen-only” feedback experience.

The high bandwidth of the piezoelectric actuator makes it capable of reproducing high-frequency transients, which are essential for very high-fidelity touch feedback. This property of piezoelectric materials can simplify the process of creating haptic drive waveforms because there is less need to compensate for the inertial actuators’ mechanical performance limitations with clever waveform design. In fact, the piezoelectric output bandwidth is far higher than needed for haptics, and components of the drive signal above approximately 400 Hz should be filtered because they may create objectionable audio artifacts without improving haptic quality. Filtering high-frequency components also reduces power consumption because the piezoelectric element presents essentially a capacitive load – a high-frequency output tends to result in high current draw.

The fast response time of piezoelectric actuators can lead to a reduction in power consumption. While there are multiple factors that contribute to the quality of the perceived haptic effect, the magnitude of the acceleration of the touch surface is a primary determinant. Because, relative to inertial actuators, the piezoelectric system can reach a given acceleration more quickly, it allows the duration of the haptic event to be shortened while maintaining the perceived quality of the effect. This can reduce the duty cycle and help preserve battery life.

One of the challenges in designing piezoelectric-based touch feedback is supplying the voltages that are required to actuate the piezoelectric elements. A range of piezoelectric architectures are available, and they can require input voltages from the tens of volts to hundreds of volts. The lower-voltage piezoelectric elements are costlier, so the design process should take into account the tradeoff between piezoelectric-element cost and drive-electronics cost.

Mechanically, piezoelectric actuators can also be more problematic to integrate. Because they are ceramic, and in the case of beams, very thin, they can be prone to breakage during handling as well as in use. The risk can be reduced by laminating the beam to a thin brass or steel shim. This process, however, increases the component cost.

Piezoelectric-based haptic touch screens are still new to the market. SMK, in conjunction with Immersion Corp., has developed and marketed touch screens with integrated bending-beam piezoelectric haptics. Immersion Corp. has also publicly demonstrated piezoelectric-actuated touch-screen technology in a prototype tablet PC.

Surface Actuation

Surface actuation is a new technology invented by Pacinian Corp. that is based on electro-attractive forces to enable direct activation of the touch surface. The principle behind the system is basic physics: an attractive force is generated between two surfaces that have a charge differential. By optimizing the surface materials, spacing, and drive signal, high-fidelity feedback can be generated on a variety of transparent and opaque materials. Though simple in principle, each embodiment is unique, and a deep understanding of the system dynamics is required to develop an optimized system.

Unlike piezoelectric-actuation systems, in which discrete actuators provide the motive forces, the surface-actuation mechanism is integrated within the touch screen or touch surface. The surface-actuation topology presents some interesting advantages over the other methods. First, it is easier to achieve a consistent response profile over the entire touch surface. Second, the actuation force scales with the touch surface area, which makes surface actuation more compelling as the touch-screen area increases. Inertial and piezoelectric-actuation methods require larger or additional actuators as size increases; with surface actuation, this is not an issue.

As with piezoelectric actuation, the touch surface moves relative to the housing, providing feedback directly to the finger touching the screen and not vibrating the entire device. Other than the motion of the surface, the only moving part is a spring element that compresses during activation and restores the surface to its neutral position when the charge is reduced (Fig. 3).

Because of the mechanical simplicity, the reliability of this haptic subsystem is very high; it has been tested to more than 200 million actuations, with no degradation in performance. As with piezoelectric systems, the system response can be very fast, with frequency response from DC to more than 500 Hz possible for small surfaces. Drive waveforms can be generated digitally or directly driven from standard audio signals. Through optimization of the travel, spring, and drive signal, the system can replicate the characteristics and perception of high-quality mechanical switches and keyboards.

The additional space required for the active layers is only slightly more than the desired travel. In a well-integrated system with a typical touch-surface displacement of 0.2 mm, the increase in thickness can be less than 0.5 mm over a standard touch screen without tactile feedback. Other than two power leads and the drive electronics, which can be located remotely, there are no actuator components that extend outside of the active surface, thereby simplifying system packaging.

Power consumption for surface-actuated systems is very low, less than 10 mW for many configurations. However, although drive voltages vary depending on design requirements, they are higher than that for other solutions. Pacinian Corp. has partnered with semiconductor manufacturers to develop a family of appropriate drive components with a small form factor and accessible cost.

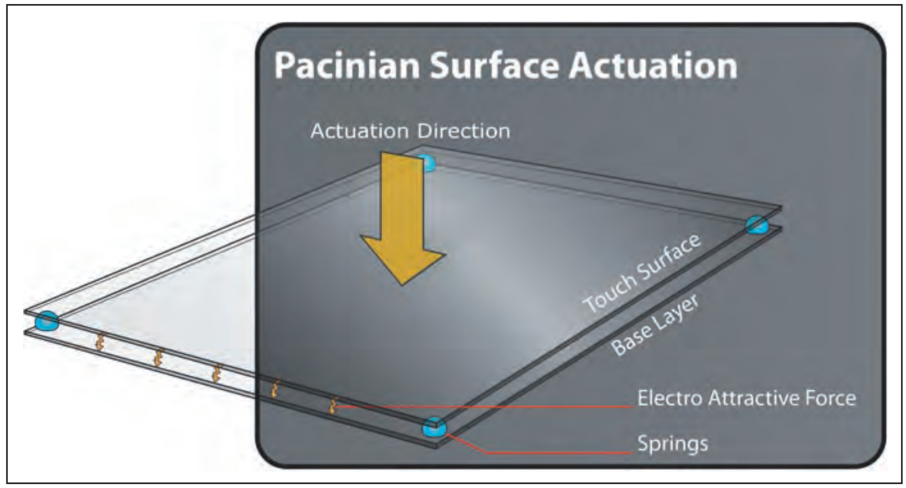

Fig. 3: Pacinian Corp.'s surface-actuation technology actuates the entire touch surface by introducing a charge differential between it and a fixed conductive surface. Source: Pacinian Corp.

Summary

In the end, there is no single haptics technology that is optimal for every application. The best choice will depend on the space, performance, usage, and cost constraints of the target device. Each technology option presents a set of trade-offs that product designers should consider:

Ease of Integration: What is the size and shape of the actuators and drive components, and how flexible are the options to physically integrate the components within the device?

Control Flexibility: How simple is it to create the haptic drive waveforms and can the waveforms be created using a variety of methods to achieve a range of haptic results?

Cost: What is the projected development and manufacturing cost for the haptic system?

Performance: How faithfully can the system recreate complex haptic effects and what is the range and perceptual resolution of the haptic vocabulary?

Power Consumption: What is the projected power consumption of the haptic system, assuming an equivalent haptic effect strength?

Technology Maturity: How market-tested is the technology?

As can be seen from Table 1, inertial actuators excel in actuating the entire device, as is common in handheld applications. However, the performance and control flexibility of newer haptic actuation technologies dominate in "touch-screen-only" haptics implementations.

Touch feedback is increasingly being implemented to improve the quality of user-device interactions and to enable a more intuitive, engaging, and satisfying user experience. In 2009, touch feedback has become a core feature in many tens of millions of consumer-electronics devices. As touch interfaces become more commonplace and device manufacturers continue to focus on the user experience as a differentiating competitive advantage, touch feedback is expected to play a leading role. There is no better time than now to evaluate how high-fidelity touch feedback can differentiate a product or service. With the multitude of solutions available, there are implementation options to meet most system requirements.

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Table 1: This chart lists the various actuation technologies and their relative advantages and shortcomings.

	Inertial ERM	***Inertial ERM***	***Inertial LRA***	***Piezo***	***Surface Actuation***
Type of Actuation	Whole Device	Touch Screen Only	Whole Device	Touch Screen Only	Touch Screen Only
Ease of integration	●●●	●○○	●●●	●●○	●●●
Control flexibility	●●○	●●○	●○○	●●●	●●●
Cost	●●●	●●○	●●○	●○○	●●○
Performance	●●○	●●○	●●○	●●●	●●●
Power Consumption	●○○	●○○	●○○	●●○	●●●
Technology Maturity	●●●	●○○	●●●	●●○	●○○

Mobile-Display Evolution: More at Your Fingertips

Mobile-display developers have been improving the quality and lowering the cost of their products as the demands on mobile devices increase.

by Paul Semenza

OVER THE LAST FEW YEARS, the handheld-device market has been transformed by waves of innovation in hardware and services – enabling mobile music, mobile video, and all forms of mobile information, ranging from Internet access to e-mail to navigation. While Moore's Law, and the digitization of all forms of content, have enabled incredibly compact devices, the requirements for displays have actually gone in the other direction – toward larger and brighter units capable of showing more information at higher quality. A complementary development has been the increasing integration of touch technology into mobile devices, thus increasing the area available for displays.

The technology and manufacturing of mobile displays have evolved to meet these needs. Specifically, advanced-generation factories for large-area TFT-LCD applications, such as TVs, have enabled panel makers to devote increasingly larger fabs to the production of mobile displays, increasing output and lowering costs, while display technologies such as low-temperature-polysilicon (LTPS) TFT-LCD and organic light-emitting-diode (OLED) technology, as well as newer technologies such as reflective displays and embedded projectors, have focused on mobile applications by offering improvements in display performance, thickness, weight, and power consumption.

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Handsets Get Bigger

For the display market, the term "mobile devices" really refers to mobile phones. As a portion of all small–to–medium-sized displays (those less than 10 in. in diagonal), mobile phones exceeded a 50% share in 2008 and are approaching 60%. The next two largest mobile applications – digital still cameras and portable media players – make up 10% of small-to-medium revenues. As the mobile phone becomes the primary device for mobile communications, gaming, video, and Internet usage, the display has become increasingly important.

In 2008, 1.4 billion displays were shipped for mobile phones, not including secondary displays used on clamshell-type handsets. More than two-thirds of these displays, or nearly a billion units, were TFT-LCD based, using either amorphous-silicon (a-Si) or LTPS TFTs (Fig. 1). Due to a decreasing price premium and the growing requirement for graph-

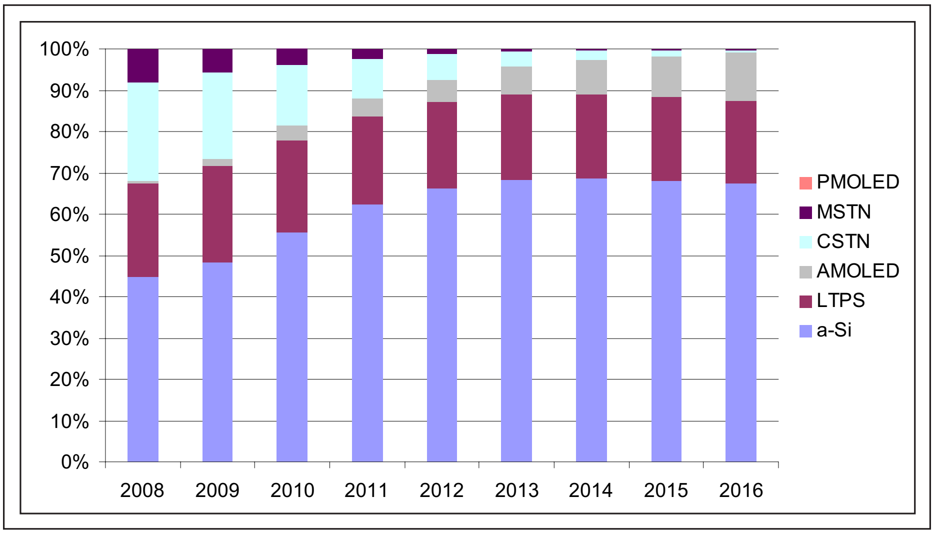

Fig. 1: Active-matrix displays – TFT-LCDs, LTPS-LCDs, and AMOLEDs – are increasing as a share of the mobile market. Passive-matrix forms such as MSTN and CSTN (monochrome- and color super-twisted nematic) LCDs and PMOLEDs (passive-matrix OLEDs) are declining. Source: DisplaySearch, Q2 '09 Quarterly Mobile Phone Shipment and Forecast Report.

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ics and video, active-matrix technologies (including AMOLED technology) will continue to grow as a share of the mobile-phone display market, and passive-matrix displays will remain only in the least-expensive phones.

TFT-LCD panels for mobile phones are mainly made in Gen 4 or smaller fabs. For the most common screen sizes (between 1.8 and 3.5 in), these fabs can make anywhere from a few dozen to more than 300 displays on each input sheet. As of 2008, 60% of mobile-phone main displays were 2 in. or smaller in diagonal (Fig. 2). Handsets are rapidly moving toward larger screen sizes, however, and by 2012, the same share will be taken up by displays from 2.2 to 3 in. Screen sizes larger than 3 in. are growing very rapidly as well, but the 2.2—3.0-in. range will continue to increase its share of the market because this size range can provide reasonably high information content while keeping the overall handset size reasonable.

A key challenge for mobile displays is to provide a high level of information (ideally, the same amount as on a desktop monitor, notebook PC, or TV) in a very small area. This requires high levels of pixel density, a requirement that has been a key driver for the adoption of LTPS technology, which allows for a smaller switching transistor in the pixel region than a-Si. The smaller transistor means less dead area in the pixel and, consequently, the display pixels can be smaller overall.

The move toward larger screen sizes is driven by users' requirements for higher levels of information content. The QVGA (320 × 240 pixels) format became the mainstream size in 2008 and will continue to grow for the next few years, as shown in Fig. 3. For the smart-phone segment of the market, HVGA (480 × 320 pixels) and VGA (640 × 480 pixels) are becoming the standard formats. New formats that are fractions of HD (1920 × 1080 pixels) are also growing, including nHD (1/9th of HD) and qHD (1/4th of HD).

Multimedia Demands Colorful, Bright Displays

The growth in mobile video, through streaming content and downloads, is creating a need for high levels of color reproduction. Color gamut is influenced by the gray scales provided by the driver IC, as well as the color-filter and backlight design. In 2008, 256K color displays (this is 6 bits per color; the potential number of colors produced is

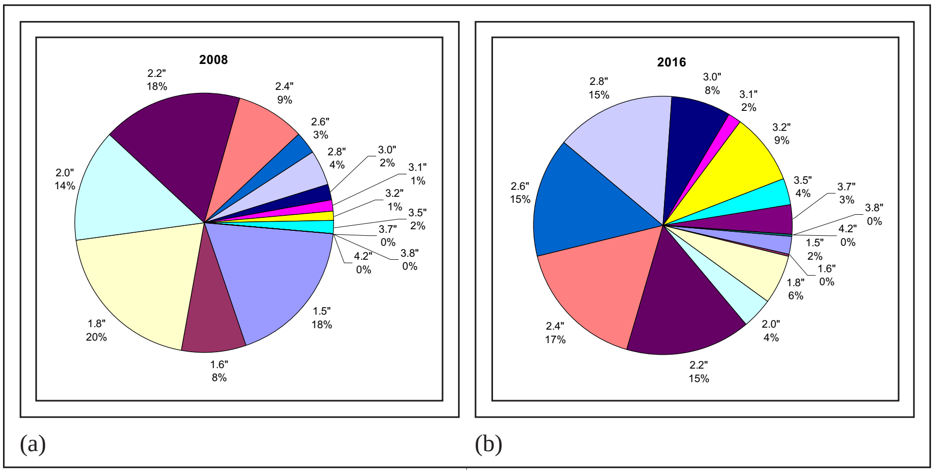

Fig. 2: *From 2008 (left) to 2016 (right), mobile-phone display screen sizes will continue to increase in terms of market share. Source: DisplaySearch, Q2 '09 Quarterly Mobile Phone Shipment and Forecast Report.*

262,144) made up half the mobile-phone market. Full-color (16.7M colors) displays recently entered the market and are likely to remain a small portion of it for the next few years. While white LEDs have become the mainstream approach, some panel makers have developed RGB LED backlights for mobile displays, which offer purer primary colors than filtered white, enabling a wider color gamut. An intermediate solution has been to enhance the red and green output of white LEDs through the addition of special phosphors. The typical mobile display will have a color gamut that approaches the NTSC standard used for TV.

In order to provide good video quality, especially in bright ambient lighting, displays need high brightness. This is another area of performance that is impacted by the display and lighting design: LTPS panels typically have higher aperture ratios, allowing more light through, and color-filter designs such as RGBW also enable higher brightness. Samsung is pursuing RGBW displays using the PenTile™ technology it acquired through Clairvoyante. Of course, the display could

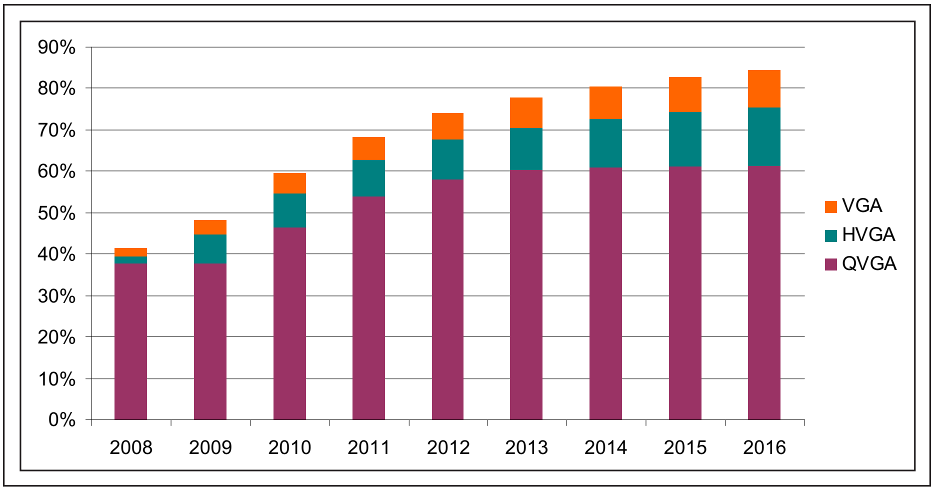

Fig. 3: *The mainstream QVGA format will continue to gain market share for the next few years. Note: QVGA = 320 x 240 pixels; HVGA = 320 x (>320) pixels; VGA = 480 x (640+) pixels. Source: DisplaySearch, Q2 '09 Quarterly Mobile Phone Shipment and Forecast Report.*

also use more (or higher power) LEDs, but this would have a direct impact on battery life. Most mobile displays currently have a brightness in the 300–400-nit range (with portable navigation devices and automotive displays significantly higher), and over the next few years displays in excess of 500 nits are likely.

Another requirement introduced by the growth of mobile video is wide viewing angle. Whereas most mobile information is viewed by one person holding the display at a normal angle, video users often have the desire to share with others, meaning that some viewing will be at off-normal angles. Thus, mobile displays now implement wide-viewing-angle technologies such as MVA and IPS, as well as different liquid-crystal modes, such as optically compensated bend (OCB) and special polarizer and optical compensation films. These approaches typically introduce additional tradeoffs because they can result in lower brightness.

Keeping Power and Weight to a Minimum

Improving visual performance through high brightness, broad color gamut, and wide viewing angle increases power consumption. The engineering challenge for mobile-display designers has been to increase performance while at the same time reduce power consumption. As mentioned previously, RGBW and similar pixel architectures enable optimization of color gamut and brightness while holding power consumption constant. Transflective design – using partial mirrors behind each pixel to reflect ambient light – also has resulted in power savings. Another approach is to manage the backlight brightness by using two forms of control. Content-adaptive backlight control (CABC) analyzes the content of the frames written to the display and modifies backlight output, dimming the LEDs when there are dark frames. Another form of backlight control uses an ambient-light sensor to determine the lighting conditions in which the display is being viewed, dimming the LEDs when ambient-light levels decrease. Because LEDs are the primary source of power consumption in mobile displays, these two forms of backlight control can have significant impact on power consumption.

As mobile displays get larger and the devices that contain them get smaller, a premium is placed on thin, lightweight displays. The primary approach to achieving these is to thin the glass substrates, which account for most of the thickness and mass. While it is technically possible to produce glass substrates thinner than the typical 0.5-mm thickness used in Gen 4 and smaller fabs, the higher cost of production and handling has been prohibitive. The most common approach is to thin the substrates after the liquid-crystal cell has been produced, either by mechanical (grinding, lapping, polishing) or chemical (etching) means. Typical thickness reduction is 0.1–0.2 mm on each substrate, resulting in a significant reduction of material. In some cases, mechanical strength is achieved through the use of an additional, chemically treated cover glass.

Mobile applications are very challenging for display reliability due to the level of shock, vibration, and other physical stresses that mobile devices typically encounter. As a result, one of the main failure mechanisms is damaged connections, particularly between the driver IC and display. Thus, integrating the driver functions has reliability benefits, another strength of LTPS technology. However, amorphous-silicon TFT-LCD designs have integrated driver functions as well. Developed by Samsung, an amorphous-silicon gate (ASG) incorporates the gate-driver function directly on the surface of the glass panel, reducing the number of components and connections, which can increase reliability and decrease cost. This technology is an indication that amorphous-silicon will continue to compete with LTPS.

Touch Adds Functionality and Performance

The most notable new feature in mobile displays has been the expansion of touch screens. Technologies such as projected capacitive, as well as new designs and user interfaces, particularly the multi-touch-based user interface developed by Apple for its iPhone, have created increased momentum of touch in mobile devices. DisplaySearch estimates that the penetration of touch screens into mobile phones will pass 20% in 2009, up from less than 16% in 2008. By 2015, touch screens are expected to be used in nearly 40% of mobile phones (Fig. 4).

Driven by the simplicity of manufacturing and low cost, resistive has been the most widely used touch-screen technology. However, the relatively poor optical transmissivity and durability of resistive have led to adoption of other technologies, particularly projected capacitive. This technology, while costing more, enables excellent optical performance, as well as the ability to design-in chemically treated cover glass, which protects the display and touch screen, and, as initiated by the iPhone, can become the entire front face of the phone. Perhaps the most disruptive touch-screen technology eliminates the touch screen itself in favor of embedding it into the TFT-LCD. So-called in-cell touch technology utilizes photosensors or voltage sensors in the TFT array, or capacitive sensing on the color-filter plate. As such, it eliminates any films or

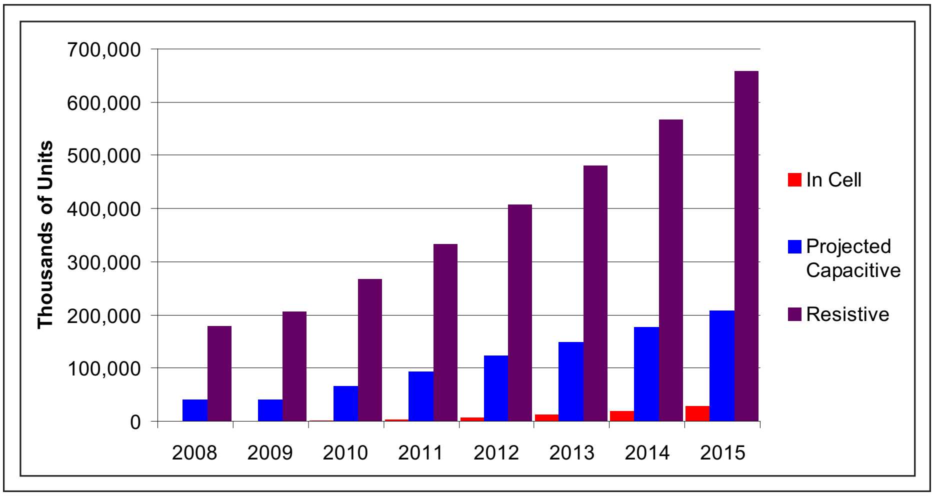

Fig. 4: *Touch screens, whether in-cell, projected capacitive, or resistive, will penetrate more and more of the mobile-phone market through 2015. Source: DisplaySearch, 2009 Touch Panel Market Analysis Report.*

glass layers required by external touch technologies, reducing the size and number of components, while at the same time increasing reliability. At present, the main challenge is the increased cost that the additional elements impose on the display by reducing manufacturing yield, but it is expected that as more TFT-LCD makers focus on this technology, they will bring down the cost.

New Functionality through 3-D and Flex

By utilizing fast-switching LC modes, optical films, or other approaches, TFT-LCD makers have developed mobile displays with 3-D functionality. The key challenges are to produce displays that have both 3-D and 2-D capability, with minimal performance or cost impact. At the same time, there is limited content (mostly gaming) that would create the demand for 3-D on mobile devices. There is some movement toward such functionality in cameras and digital photo frames.

While it will be a long time before fully functional mobile devices are mass-produced in flexible form factors, there are benefits to using flexible displays. When constructed with rigid plastic, plastic film, or metal foil, displays can be made more rugged and lightweight. Current flexible-display technology is not mature enough to be full color and video capable, but simpler displays (such as e-paper devices) are in production. Flexible-display technology was used, albeit in a rigid form, in the Motorola Motofone, but that product was removed from the market due to lower resolution than required to use the phone for text messaging. However, flexible-display technology is being utilized in other ways, such as the Samsung Alias 2, which utilizes E Ink's electrophoretic technology to enable a dynamic keypad that changes depending on whether the phone is used in portrait or landscape mode (Fig. 5).

Fig. 5: Samsung's Alias 2 mobile phone uses display keys based on E Ink technology.

Future Technologies

While TFT-LCD technology is increasing its dominance in the mobile-display market, the demand for lighter, lower-power, higher-performance displays continues to draw in new technologies. In addition to OLED and electrophoretic technologies, several companies are developing alternatives to LCDs. One class of devices utilizes microelectromechanical systems (MEMS) to selectively reflect colors from an external light source or to "shutter" light from LEDs. These devices have simpler architectures because they do not incorporate the liquid crystal and associated optical films. However, as the long effort to bring OLED technology into mobile devices indicates, simplicity does not necessarily mean that other manufacturing or materials challenges do not exist.

Societal trends mean that workers and consumers alike are more mobile in their technology usage. The significant upgrades in wireless technology around the world, including 3G and higher cellular technology and WiFi networks, is bringing the notion of "access anywhere" closer to reality. This means that our mobile devices will become increasingly important. The demand for mobile displays – and the demands on them – will both continue to increase. ■

The Approach of 4G

The next-generation mobile network will offer bigger, better, faster bandwidth and is being promoted as enabling "anytime, anywhere, anything" in terms of content. How will this type of connectivity actually come to pass and what does it mean for mobile-device displays?

by Jenny Donelan

EVERY TECHNOLOGY has its Next Big Thing, and in the world of mobile communications, 4G is clearly a contender for the title. Service providers such as Sprint/Clearwire and Verizon have announced rollout plans for the next generation of mobile service, which is by definition a mobile Internet service. With 4G fully deployed, users wielding the appropriate devices will be able to download and watch movies, share photos, browse the Web, and, in general, conduct any type of electronic business imaginable in near real time – wherever they like. With 4G, users will be able to loosen their ties to home or office computers and enter a world of limitless connectivity and entertainment on demand.

Such is the promise of the next-generation network. And judging from the popularity of Apple's iPhone and other smart mobile devices, the service will be feeding at least a specific sector of the public that is increasingly hungry for mobile data. But how soon 4G will become reality depends on several factors – the carriers' ability to build out the 4G infrastructure, the devices' ability to handle the content, and the desire of a large-enough base of users (beyond early adapters and teenagers) to actually employ mobile devices in these ways.

4G Definitions

To begin with, what actually is 4G? In plainest terms, it stands for the fourth generation of wireless communication, with 1G being analog mobile phones, 2G the first digital generation, and 3G the network capabilities that we are supposedly enjoying right now. However, although 4G is also often referred to as the "next generation," most users are not even using third-generation technology yet, so 4G is, for the majority of us, the "generation after the next generation."

A precise definition of 4G's benefits is equally difficult to pin down. According to a recent Sprint press release, it is "… a turbo-charged mobile broadband experience with wireless connectivity 3–5 times faster than today's 3G from any carrier." [1] Many industry experts agree that the term is somewhat nebulous. "4G is not well-defined," says Barry Young, Managing Director for the OLED Association, "although it will enable a whole new set of devices and capabilities." Perhaps the best way to view 4G is in holistic terms. The organizers behind the first 4G World Conference and Expo, held in Chicago in September of this year, describe their event as "dedicated to the entire landscape of next-generation mobile networks from infrastructure to devices, applications, and content" (www.4gworld.com). Viewed this way, 4G is a sort of ecosystem of the future of mobile Internet.

One thing is definite: 4G will be fast. How fast is hard to say, but certainly faster than the wireless Internet most of us experience today. While 3G's data-transmission speeds are between 600 kbps and 1.4 Mbps, 4G speeds start at around 2 Mbps and may at some point reach 10 times that speed. This should enable faster, smoother file sharing and downloading – even high-definition movies would become feasible as content. 4G networks are also designed for distance, offering service in terms of square miles instead of feet (as is the case with most Wi-Fi networks today). The official coverage range for a typical 4G access point, for example, is about 30 square miles. Due to the bandwidth used, the equipment, and other considerations, the actual range will probably be considerably less, but wider than current Wi-FI by far.

Several specific technologies or platforms have been developed to realize the 4G ecosystem. Of these, the two major players at present are Worldwide Interoperability for Microwave Access (WiMAX) and Long-Term Evolution (LTE). Each has been developed to move data rather than or as well as voice, and each forms the basis for an IP network based on orthogonal frequency-division multiplexing (OFDM) technology, which is a digital multi-carrier modulation method. And each has its proponents. Sprint's 4G network is based on WiMAX, as is its business partner Clearwire's. Verizon and AT&T have chosen LTE. (For more description, see the Sidebar "WiMAX and LTE.")

As stated above, these platforms are similar at the core. In fact, some observers predict a convergence in years to come. In general, though, WiMAX is farther along commercially than LTE, whereas LTE is thought to have more powerful backers and more backwards compatibility with existing networks (at least in Europe). LTE is also faster, but WiMAX is working on a new standard that will make it comparable.

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When Will It Arrive?

Citizens of Moscow and St. Petersburg, Russia, were introduced to 4G from Cisco early this year. The rest of Europe and Korea have also been in the vanguard compared to the U.S. Sprint piloted a 4G network in Baltimore last year. Otherwise, in the U.S., for those living in Atlanta, Las Vegas, or Portland, Sprint's 4G network has recently come to your town. Sprint and other carriers have announced 4G rollouts in several other U.S. cities before the end of 2009. So it would seem that 4G is poised to become a reality.

Yes and no – it will be used as a broadband Internet service before it becomes the mobile device platform of choice. The first 4G-enabled device that Sprint has offered for sale is not a mobile phone but a modem (Fig. 1). Currently, there are no 4G phones on the market in the U.S. Nokia and LG are rumored to have prototypes of 4G devices, but photos of those are few and far between and have appeared only in unofficial blog postings.

It is also possible that users are not ready for 4G. According to Richard Murphy, research analyst in the Wireless and Mobile Communications group at IDC. "Right now, in the U.S., there are approximately 278 million mobile-phone users. And for all the emphasis on 4G these days, only 25–30% are even using 3G."

Fig. 1: *This print advertisement from Sprint shows its first 4G/3G mobile broadband device – a modem. Image courtesy Sprint.*

Are users going to be willing to make the leap from second generation straight to fourth generation, he asks. "And how much are they going to be willing to pay for 4G?" AT&T discovered with Apple's iPhone, he continues, that the top per-month price consumers seemed to be willing to pay for the privilege of using the device was $90–100. Even so, while it is a great convenience to be able to look up restaurant reviews and directions in a strange city (to cite some of the more popular and useful applications for these devices), how many people are willing to pay for the convenience, let alone for more content at perhaps an even higher premium? "The average user," says Murphy, "is not at a point where streaming TV or even surfing the Web is a primary driver. Data revenue is still about 25% [of total] for carriers."

4G Devices

That said, there was a time when experts said that TVs were a passing fad – why would anyone want to watch something on a small screen at home when they could go to the movies? So it behooves display makers to make preparations for the Next Big Thing. And, in fact, they are already doing so, though they are probably not seeking 4G solutions specifically – they just want larger, sharper, more-colorful displays that use less power, regardless of the platform.

When *Information Display* asked various entities in the display business how 4G was likely to affect R&D, the answers varied. The OLED Association's Barry Young said "4G is not likely to have a leading-edge kind of impact on OLEDs." But, he added, the fact that users will be doing more video could lead to a more OLED-friendly device environment. "What we're seeing now is displays getting bigger and bigger," says Young. "And one could envision that in a 4G device you could have the equivalent of a DVD player." That could be a good opportunity for OLED technology's vibrant color, low energy drain, and ability to handle motion, he notes.

Jim Cathey, Vice-President of Business Development at Qualcomm (and author of an article in this issue), believes that the additional applications that 4G could bring about may well have some kind of an impact on display technology. "Your handset could become a DVR for high-definition video," he says. "For example, I travel a lot, and I would love to have my shows taped and then play them on the handset or connect them to a display in my hotel room." Similar to OLED technology, his company's MEMs-based mirasol displays might be a good choice for this type of application, he says, but again, it's along the direction his company is already pursuing.

However, it is good to keep in mind that the conundrum raised by 4G – devices will have larger, thinner displays capable of showing color and moving imagery, which will compel people to use the devices for longer periods while viewing content that is power hungry by its very nature, which will drain batteries faster than ever – is the same conundrum faced by display makers today. So, the emergence of 4G is not likely to cause an explosion on the display scene because the display-size *vs.* battery-drain situation already exists and is, in fact, the subject of most of the articles in this issue of *Information Display*.

Coming (Somewhat Soon) to a Mobile Phone Near You

"4G is something that many people are excited about," says IDC's Murphy. But it's still a ways off. We could be 5 years off. The network still has to be built." As it is, the 3G network itself has to get up to speed. In early September, *The New York Times*[4] ran an article about how intensive iPhone use in particular geographic areas can overload a network. The author even compared the iPhone to a Hummer (among cell phones), noting that excessive numbers of the devices in use in a particular area clog the information highway and lead to dropped calls and spotty service. The carrier involved was AT&T, and other carriers are quick to claim that they do not, or will not, have such problems. Only time will tell. However, it is probably safe to say that the displays in mobile devices are not going to be any kind of gating factor for 4G's adoption. Says Paul Semenza, analyst with DisplaySearch, "The bandwidth is kind of catching up to the displays."

This is a fact that has not gone unnoticed by carriers. In fact, the whole infrastructure issue is one of the selling factors of 4G. Nokia's literature, for example, refers to the need for

WiMAX and LTE

WiMAX is based on the open-standard IEEE 802.16/ETSI HiperMAN and overseen by the WiMAX Forum, a not-for-profit established in 2001 with the goal of certifying and promoting the compatibility and interoperability of broadband wireless products based on the above standard. The WiMAX platform has a head start over LTE in terms of deployment; according to the WiMAX Forum, there are currently 502 WiMAX networks operating in 145 countries. Networks began rolling out in the U.S. in late 2008 and early 2009.

In theory, WiMAX can move 75 Mbps of data, although in actual practice, speeds will be much slower. According to Clearwire, Silicon Valley developers participating in its CLEAR 4G WiMAX Innovation Network initiative (announced in September 2009) can expect peak download speeds of up to 10 Mbps, with average download speeds of 3–6 Mbps. Major players behind WiMAX at present include Bright House, Comcast, Sprint, Time Warner Cable, Cisco, Intel, and Google.[2] For more information, see www.wimaxforum.org.

LTE is a Third-Generation Partnership Project (3GPP) started in 2004 to enhance Universal Terrestrial Radio Access (UTRA) and optimize 3GPP's radio-access architecture. The 3GPP is a collaborative group of international standards organizations and mobile-technology companies. LTE is widely considered to have an edge in terms of muscle because it has a great deal of worldwide commitment from Global System for Mobile Communications (GSM) carriers. GSM is used in Europe and in other parts of the world. However, LTE-based service is just gathering launch momentum in the fourth quarter of 2009. Verizon and AT&T are behind LTE in the U.S. and Nokia is a prime mover in Europe. In Germany on September 18, 2009, Nokia Siemens Networks made the first-ever call on a next-generation 4G LTE network.

LTE is speedy. According to a release from Nokia, "The targets for LTE indicate bandwidth increases as high as 100 Mbps on the downlink and up to 50 Mbps on the uplink." [3] Most industry experts, however, predict that a real-world per-user expectation might run closer to the single digits. For more information, see http://www.3gpp.org/article/lte.

increased capacity in light of growing demand. A plus for its LTE 4G platform, it notes, is "the reduced capital and operating expenditures it requires over previous 3G networks. A key aspect of LTE is its simplified, flat network architecture, derived from it being an all-IP packet-based network, and the use of new techniques to obtain high volumes of data through a mobile network." [3]

Sprint, on its part, is saying that its roll-out is going to enable a better, more dependable experience for users. "What we're doing for 4G is building an entire network from the ground up," says spokesperson Stephanie Vinge-Walsh.

Whenever it does arrive, and whether it is based on WiMAX or LTE or something else, 4G's increased speed, bandwidth, and distance capability should eventually bring about a new type of connectivity. These days, for example, if you want to check your e-mail at the airport or in a city, "You have to hunt around for a hotspot," says Vinge-Walsh. But 4G can be deployed across a much larger area. To explain WiMAX, she says, she tells people, "You'll have a hotspot the size of a city. That really kind of resonates."

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Effect of gas pressure on permanent dark image sticking on a bright screen in AC plasma-display panels (pages 981–987)
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The *Journal of the SID* is planning a Special Section to be published during the fourth quarter of 2010. **We are soliciting original contributed papers describing advances in 3-D/2-D Switchable and Multiview Display Technologies.** Suggested topical areas include:

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can offer. Similarly, I also believe that those of us who focus on display systems and components would enjoy reading more about what is happening in the broader industry around us. It is for these reasons we are creating two new feature categories that we have titled "Making Displays Work for You" and "Enabling Technology." In the former feature you will now find regular monthly articles focused on the application of display technology, including how-to features and tips on ways to get more out of display components in new and existing designs. In the latter case, we'll be looking outward into the electro-optical industry and identifying those technologies that may have a meaningful impact on the requirements for display components or the demands on new products using displays.

We have also been listening to our customers and recognizing that a magazine focused purely on technology, especially in today's economic climate, is not giving our readers the full picture. That's why we have added a monthly feature titled "The Display Marketplace," in which we plan to cover many current events from a business perspective and provide an economic context for what may be happening in the industry. These articles will tackle tough business issues and focus on helping our readers better navigate the display marketplace.

However, while we have made these changes, we have not strayed too far from our original purpose and will still be providing our conventional technology-intensive features each month under the "Frontline Technology" header. Here, we will continue to offer the carefully researched, objective, leading-edge display technology articles we have always provided, still contributed by leading scientists and engineers from our industry. So, in effect, we have added much more value to the same familiar product and that should be an improvement everyone can appreciate.

This month our technical theme covers a variety of topics related to displays for mobile and hand-held devices. In our first Frontline Technology article, "Enhancing Mobility through Display Innovation," author Jim Cathey from Qualcomm provides a comprehensive survey of the needs, both met and unmet, for displays in mobile devices and then describes the state of the art in microelectromechanical systems (MEMS) as a possible solution to those needs. I was recently invited to visit the Qualcomm laboratories in San Jose, California, and was very impressed with the technology as well as the care and attention the team puts into its work as researchers. I think you will find this a very interesting read.

We also have a comprehensive article from Sharp Corp., written by Kiyoshi Minoura, Yasushi Asaoka, and others describing their latest work in "Making a Mobile Display Using Polarizer-Free Reflective LCD and Ultra-Low-Power Driving Technology." This article is a follow-up to an earlier paper given at Display Week 2009, with new information that shows how compelling a solution their technology may be. I'm very bullish on the opportunities for reflective technology because of the inherent power savings and reduced packaging demands for mobile devices. These innovations can keep LC technology on the forefront for reflective applications.

Making displays work sometimes involves making better user interfaces and we have all seen persuasive evidence that touch screens are here to stay. It's hard to find any hand-held product paradigm today that does not involve touch. However, as we also know, touch interfaces do not provide the same user experience that keypads do. Haptics refers to technology that interfaces with the user via the sense of touch by applying forces, vibrations, and/or motions. Researchers have been working on haptic devices in conjunction with touch for a long time, but very few successful implementations have reached the marketplace. In their article titled, "Haptic Feedback Solutions for an Enhanced User Experience," Pacinian Corp.'s Michael Levin and consultant Alfred Woo explain why this has been the case and how recent advances in the technology can be used to enable a new generation of haptic-enabled interfaces for many applications.

The Display Marketplace this month is analyzed by longtime friend Paul Semenza from DisplaySearch, who evaluates the technological innovations in the world of mobile devices and gives us his prediction on the requirements for displays and touch screens for the foreseeable future.

Finally, this month we take a closer look at 4G wireless technology and examine what impact it is likely to have on requirements for displays in mobile devices going forward. Beyond the obvious increased demands on battery life and pixels, there appears to be some new wrinkles worth thinking about, not least the idea that the immediate requirements of 2.5G- and 3G-based mobile communications devices have yet to be met in terms of available bandwidth. I'm very pleased with the work our own Jenny Donelan put into this feature for us.

I hope you all enjoy this first issue in our new format and as mentioned earlier, we do this to please all our customers. We welcome your feedback, so please take the time to send your comments and suggestions to us at press@sid.org. ■

industry news

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(about $US1600) in Hungary to a maximum penalty of 15 million Euros and 10 years in prison in Ireland. Fines have been levied in Europe and products recalled. In practical terms, however, perhaps the biggest setbacks for non-complying companies are sales bans, loss of contracts, and negative publicity. Companies are starting to prefer to do business with companies that are compliant. The negative aspects of getting caught not complying seem to outweigh any financial and practical benefits of avoiding compliance.

One of the biggest challenges to companies in terms of compliance is end-of-life legislation. Manufacturers are going to have to figure out how to collect and recycle (and induce customers to recycle) their products on a global basis without losing money. Some cross-company collaboration efforts are already being made in this area, and, of course, recycling represents a new opportunity for third parties willing to figure out the logistics. The upcoming final installment in this series of green-manufacturing news articles will look at end-of-life issues and the practical solutions some companies and organizations are proposing and enacting. ■

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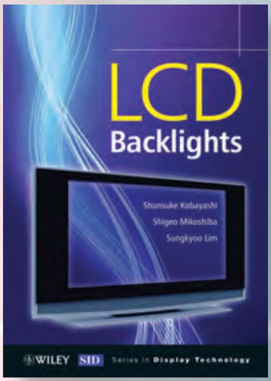

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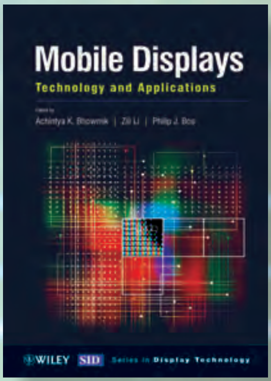

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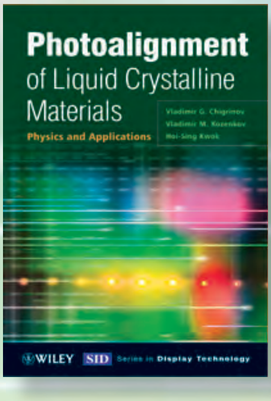

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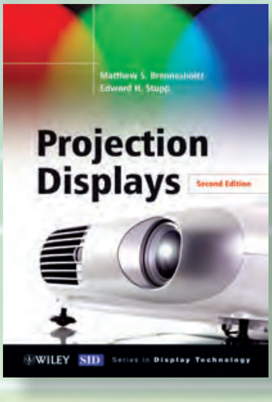

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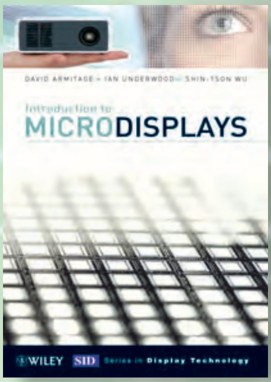

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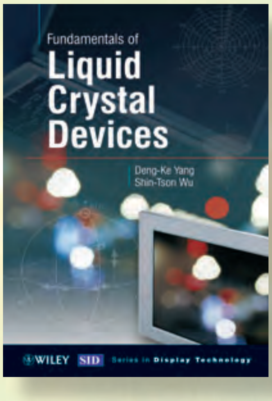

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