**think.**

**learn.**

**Engage.**

**SUCCEED.**

_Nature_ has been **reenergised and strengthened** in print and online. Now it’s even easier to stay abreast of the most **important developments in science**, and those that matter most to **your scientific career**.

_Nature_’s **new modern package** includes opinionated editorial content, vivid page layouts, improved navigation and mobile apps that position us, and you, at the **center of the scientific discussion**.

Don’t miss another week. Rediscover your _Nature_ today.

[nature.com/rediscover](http://nature.com/rediscover)
Great expectations

Display technologies can be found in almost all aspects of our daily lives, with electronic displays now being included even on objects that have traditionally never featured screens, such as kitchen appliances. Without a doubt, electronic books (e-books) are the success story of 2010. According to Amazon.com, sales of e-books have now exceeded those of hardback books, and it is display technology that has made e-book readers a practical option in terms of their readability and battery life. Most of these devices feature a black and white electrophoretic display technology developed by E Ink (see page 748), a company that started after its founder ran out of books to read on holiday. What makes these displays different to other types of display is their bistable nature — power is only needed when turning a page. The demand for these low-power displays is now bigger than ever, and consumers are eagerly awaiting the deployment of improved versions that are full colour, have better contrast or feature a larger screen size. Munisamy Anandan, president of the Society for Information Display, believes that e-readers are a big growth opportunity, not only for new display technologies, but also for LED backlights (see page 756), which help to improve the power efficiency and colour rendering of LCDs.

New display technologies are also enabling other innovative applications. Light Blue Optics has combined holographic projection technology with infrared touch-recognition technology to make a pico projection system that allows users to interact with the projected content (see page 750). Finding applications for such an ingenious technology requires little imagination — you could do your internet shopping by projecting the website onto the table and choosing the items you want by touch, or project an interactive presentation onto your desktop at work.

The pico projection market is also a growing opportunity for microdisplays made using liquid crystal on silicon (see page 752). UK company Forth Dimension Display pioneered this technology, and its products are now used in a variety of applications including in the military, medical and movie industries. Displays are everywhere, and new technologies are constantly emerging. Who knows what the next applications for displays will be?
LCD manufacturers face price crisis

After months of price cuts, manufacturers of large-size liquid-crystal displays (LCDs) are under pressure to reduce panel prices further, following a major build-up of inventory. A recent report from US business analyst iSuppli revealed that the second quarter of 2010 saw the manufacture of 52 million large (ten inches and above) LCD television panel shipments, but the sale of only 38.7 million LCD television sets. The resulting imbalance between supply and demand is having a strong impact on the sector.

“This gap is higher than anything seen in 2009. Over-supply persisted in the first two months of the third quarter as buyers cut orders in July and August,” says iSuppli analyst Sweta Dash. “LCD television brands are expected to lower prices more aggressively to reduce their inventory levels, thus putting mounting pressure on panel suppliers to reduce prices further.”

Dash points out that manufacturers of monitor and notebook panels have been reducing supply to mitigate excessive inventory levels, and that panel prices are now stabilizing as a result. In contrast, high depreciation costs at relatively new LCD television panel fabrication plants mean suppliers have been less willing to reduce production.

However, Dash predicts that the potentially strong sales of LCD television sets in China could reduce inventory levels and help to steady panel prices by the end of the fourth quarter of 2010.

At the same time, rapidly rising sales of smart phones and tablet PCs are predicted to see the global market for small- and medium-size thin-film transistor (TFT) LCDs expanding at its fastest pace for three years. According to analyst Vinita Jakhanwal, also from iSuppli, global shipments of TFT LCD panels are set to rise by 28.1% in 2010, from 1.8 billion to 2.3 billion units.

“Sales of smart phones and tablets are booming thanks to the iPhone, iPad and other competing products,” explains Jakhanwal. “Smart phone manufacturers are now adopting TFT LCDs that use in-plane switching technology, which supports a wider viewing angle and better picture quality than a conventional LCD.” But the fast-paced market expansion probably won’t last, predicts Jakhanwal. “Growth in TFT LCD shipments will slow in 2011 and beyond as the expansion of smart phone and tablet markets cools to more normal levels.”

Smart phones speed AMOLED take-up

The adoption of touch-screen technology in the mobile phone industry is fuelling the demand for active-matrix organic light-emitting diode (AMOLED) displays, reports US market research firm DisplaySearch. AMOLED displays have been the only technology in the mobile phone display market to increase revenues every quarter this year, as both unit shipments and average prices have risen. “With an average worldwide market penetration of mobile phones at 70%, manufacturers are eager to introduce new features such as touch-screens to ensure continued growth this year,” says Calvin Hsieh, research director at DisplaySearch. “The success that AMOLED displays are finding in high-end smart phones reflects these trends.”

AMOLED technology rose in popularity after its integration into mobile phones manufactured by Samsung and HTC. In the first quarter of 2010, the average screen size for an AMOLED display exceeded three inches, which is larger than that of competing TFT LCDs. Taiwan-based display manufacturers AUO and Chimei Innolux are scheduled to start mass-producing AMOLED displays in 2011. Hsieh believes AMOLED technology will now see increased year-on-year growth, although TFT LCDs will still ship more units.

Nanosys unveils Korean facility

US-based quantum-dot and materials developer Nanosys has opened a new facility in Gyeonggi-do, Korea, to support its recent expansion into the Asian market. Led by former LG Electronics vice president Jong-Uk Bu, Nanosys Korea will develop ‘architected materials’ for Asian electronics manufacturers, including high-performance LED backlights for displays and silicon composite anode materials for use in lithium–ion batteries. Earlier this year, Nanosys unveiled QuantumRail, quantum-dot-based LED backlighting units that improve LED backlit display colour gamut and efficiency. Nanosys says that its quantum dot LED technology makes it possible to deliver saturated red, green and blue colours that exceed the NTSC 1953 guidelines for displays. This latest announcement follows collaborations with Korea-based electronics manufacturers LG Innotek and Samsung Electronics to develop display products based on quantum-dot crystals.
To minimize sticking, Tae and his colleague treated the MgO layer of a 50-inch, high-definition, alternating-current PDP with radiofrequency plasma. Experiments with several gas compositions indicated that treatment with an argon plasma was most effective at preventing impurity build up. “Organic matter on the MgO layer was remarkably reduced compared to the panel that didn’t have this plasma pre-treatment,” says Tae. “The display luminance difference was considerably reduced, meaning no temporal image sticking.” Tae asserts that the plasma treatment can be used on a commercial scale. “Thanks to fewer impurities, the treatment considerably reduces the panel ageing time,” he said. “This would reduce the cost of a PDP panel despite radiofrequency plasma equipment costs.”

Image sticking

Plasma display panels (PDPs) suffer from temporal image sticking, whereby a faint outline of a previous image remains visible on the screen after the image has changed. Researchers from Kyungpook National University, Korea, have now identified why this happens and how to stop it.

According to Heung-Sik Tae, temporal image sticking is due to organic impurities that remain on the MgO protective layer in the PDP. The vacuum ultraviolet discharge during PDP operation dissociates the impurities into carbon and hydrogen, and the hydrogen then combines with oxygen from the MgO surface to form water, which causes the sticking.

A new method of controlling the viewing angle of a liquid-crystal display (LCD) promises greater privacy to users of mobile phones and laptops. By inserting a blue-phase liquid-crystal (BPLC) layer into an LCD, Shin-Tson Wu and colleagues from the University of Central Florida, USA, were able to tune the viewing angle of the display continuously when adjusting an applied voltage.

According to Wu, the BPLCs have submillisecond response times, enabling the user to switch from a wide viewing angle to a narrow one quickly. The BPLC layer is also easy to incorporate, as it is simply inserted above or below the LCD and does not require an alignment layer. Simulations were performed on a nematic in-plane switching cell, but Wu is confident that the set-up will operate in all display modes without affecting transmittance. “As long as the LCD is initially well compensated, the viewing angle can always be controlled by the applied voltage of the inserted BPLC layer,” he explains. “This method has a larger aperture ratio and higher optical efficiency than other techniques, although we now want to widen the tuning range and lower the operating voltage.”

Image sticking

Researchers from the University of Cincinnati, USA, have demonstrated, for the first time, a colour electrowetting display device based on a vertical-stack pixel structure. Producing higher resolution images than conventional layouts and with typical switching speeds of 10 ms, the design holds promise as a display for video-compatible colour e-book readers. Most e-book readers use low-power electrophoretic displays, but their low switching speeds are not compatible with displaying animation and video. In contrast, the electrowetting reflective display offers video-rate switching speeds, although current designs require the use of an overlay colour filter, limiting resolution. Now Andrew Steckl and colleagues have adopted an approach in which three pixels, filled with coloured oils, are stacked on top of each other. Arrays with as many as 1,000–2,000 pixels were fabricated. “The device has smaller effective pixel sizes than conventional layouts, leading to potential higher resolutions,” says Steckl. “We don’t need colour filters, which is a big plus, but must have good vertical alignment between pixels.” The team says that it now plans to improve colour saturation using different dyes. “We also want to develop larger arrays and use flexible substrates for the e-book reader market,” adds Steckl.

Speckle reduction

Rear-projection laser displays deliver colourful images with unprecedented resolutions, but ‘laser speckle’, an interference pattern generated at the screen, has delayed commercial adoption. A recent method reduces the problem by using a small rotating plate to diffuse the light before it passes through a microdisplay and is projected on a screen. Tatsuo Uchida and colleagues from Tohoku University, Japan, performed experiments to determine how speckle is reduced using such a set-up. They identified two occurrences of speckle in the system, the first at the rotating plate and the second at the screen. Further investigations revealed that when the plate was rotated, the granular pattern of speckles generated there corresponded to coherent regions of the secondary speckle, at the screen. The researchers then measured the speckle contrasts at the screen by changing the degree of granularity of the primary speckle.

“In every case, as granularity increased, the corresponding speckle contrast increased,” says Uchida. “This shows the degree of granularity of the primary speckle is the key parameter in speckle generation on the screen, and can be used as a unified index when discussing speckle reduction effects.”
Emergence of the e-book

Electronic books have really begun to take off in the past few years. Siân Harris finds out about a display company that has helped this to happen.

A decade and a half ago, Joe Jacobson, a professor at Massachusetts Institute of Technology (MIT), was enjoying a relaxing holiday when he realised that he had run out of books to read. Although this is a fairly common situation that many are familiar with, Jacobson’s response to it was not. The idea that struck him on holiday was that of a book that could refresh itself with new content, and so, when he returned to his lab after his break, he began work on a concept he called ‘radio paper’.

In the past couple of years, Jacobson’s idea has become a reality on a grand scale with electronic books (e-books) achieving mass market success. The Sony Reader, Amazon Kindle, Hanvon WISEreader and Barnes & Noble Nook are all now best-sellers for their respective companies. However, when the company E Ink, which designs the paper-like displays used in the majority of today’s e-book readers, was established on the basis of Jacobson’s work at MIT in 1997, such products and the accompanying market were little more than a holiday dream.

The challenge that the new company initially set out to tackle was to make displays that could mimic printed paper. This is an important issue if people are going to comfortably read whole books electronically. As Sriram Peruvemba, vice president of global sales and marketing for E Ink, pointed out: “There was a US$400 billion publishing industry producing content that is very readable but not changeable and also a very big display industry producing LCDs that are changeable but not easy to read.”

Traditional displays are uncomfortable on the eyes if they are looked at for prolonged periods, because they are backlit. The backlighting also means that they require continual power whenever they are on and indeed in many portable electronic items the display is often a power-hungry component that limits the battery life. E Ink’s aim was to commercialize a display that does not need a backlight but instead uses reflected ambient light in the same way that printed paper does.

E Ink’s displays accomplish this feat by containing a flat, two-dimensional array of microcapsules, each of which is just a few micrometres thick — about half the thickness of a human hair — and contains white and black particles. The white particles are the same as the pigments used to make paper white, and the black particles are the same as those used in ink. Where things differ from printed paper is that the particles are electrically charged: one set is positive and the other is negative. When the backplane electronics apply voltage to the microcapsules, one set of particles is driven to the top of the microcapsules and the other set goes to the bottom. The particles comprising this ‘electronic ink’ remain in this state until a signal is applied to change what is displayed. This means that readers can leave the device and return to it a few hours later without losing their page or consuming any power. In fact, E Ink turned off the power to one of its displays in 2001 and the text on that display is still readable today.

To make displays, E Ink’s microcapsules of black and white particles are coated onto rolls of plastic with an indium tin oxide conductive layer, which acts as a transparent electrode. These single-microcapsule layers are less than 400 μm thick but can be several kilometres long. They are cut into different sizes and shapes for customers, who layer the pieces onto the same types of backplane electronics that are used for liquid-crystal displays (LCDs).

E Ink’s initial applications were in areas such as signage and wrist watches, where there was already a market for power-efficient displays. However, the company did not forget its original goals, and in 2004 decided to focus on the e-book market, despite that market not really existing at the time.

The market immaturity was illustrated in 2005, when E Ink entered a partnership with Sony to help the Japanese company make its first e-book reader, the Librié, which was launched only in Japan. Unfortunately, as Peruvemba conceded, this product was not successful. At the time, there was little content available and not much awareness of electronic reading. In addition, broadband access and wireless technology were not as advanced as they are today. However, E Ink and Sony did not give up, and launched an improved version of the product worldwide in 2006–2007 to a much better response. Today, E Ink’s display technology is found in at least 90% of e-book readers, some 50 products around the world.

Creating displays that mimic printed paper is not without its challenges, of course. Improving contrast was a key target for the company. Early versions of the display gave a contrast of six to one, which is roughly comparable to newspaper print. Now the technology has reached a minimum contrast of ten to one, which is better than that of a paperback book. It is still not the contrast of pages printed on a laser printer, though, and this is one of the future goals of the company.

The company is also working on the technology’s speed of response for changing the image being displayed. One of the criticisms of early e-book readers was that they took too long to ´turn the page’. “What is fascinating with our displays is that even with the old versions they actually refreshed more quickly than users would turn the pages of a print book,” observed Peruvemba. “However, when you are turning printed pages your eyes are watching your fingers so you don’t notice this time. With an e-book reader you are just waiting so it seems like a long wait, particularly when people are used to the response times of the LCD screens on their laptops.” The response time...
In E Ink’s technology, a layer of microcapsules includes oppositely charged black and white particles. Either the black or the white particle rise to the top of the microcapsules, depending on the voltage applied at the backplane.

For E Ink’s displays is currently 250 ms, although Peruvemba said that the company has achieved responses in the lab that are ten times faster. “Today we can do animations with our displays but not video,” he said.

Response times are longer for electronic ink displays than for LCDs because of the underlying technology. With electronic ink, the fundamental constraint on response time is how fast the particles will separate and settle down. Users can begin to see the image after 60–80 ms but it takes much longer for the particles to settle and the image to become clearer. This process is also temperature dependent; the particles take longer to settle when it is colder. However, this can be offset by applying a greater voltage when the temperature is lower.

A core part of E Ink’s electronic paper products is management software, called Waveforms, that senses temperature and dozens of other parameters and adjusts the display’s operating conditions accordingly. This software also ensures that only the pixels that need changing are changed from frame to frame. This helps the images to become obvious more quickly and saves power. This feature is particularly important for showing animations and, in future, for showing video.

Peruvemba believes that one of the key markets for e-book readers will be e-textbooks. This market brings additional challenges for the e-book readers and their displays. Users want to be able to write on the device with a pen as well as to use touch input, to highlight pieces of text and take notes. This can be done using an inductive pen and a digitizer, and is being pursued by E Ink in partnership with the digital pen technology company Wacom.

Another challenge with e-textbooks is that the glass of the display could shatter. E Ink is working with partners to develop more rugged, flexible displays. The company’s signage products are already flexible but this is more of a challenge with e-book readers because of the need for matrix displays to be supported by backplane electronics that are currently made on glass substrates. Flexible e-book reader displays are currently being developed on a pilot scale and the company hopes they will begin to be mass produced later this year.

The company is aiming for mass production of colour displays also by the end of the year. E Ink’s colour displays are based on the same idea as the black-and-white displays, and use the same black and white particles in the microcapsules. The microcapsules in each pixel are then divided into four subpixels, each with a different colour filter — red, green, blue or white. For the pixel to display as red, for example, the microcapsules under the red filter need to show the white particles, which reflect the light, and the microcapsules under the other three filters show black. As they use the same underlying technology, the colour displays have power consumption similar to that of the black-and-white displays.

As with any consumer product, cost is a key factor and one Peruvemba feels the company has been successful in addressing. “There are e-book readers on the market being sold for US$150. In contrast, LCD-based smartphones sold without network contracts could be US$500,” he commented. However, he observed that even if the company gave away its displays, e-book readers would still not drop to the desired US$100 price point at the moment. This is because of the many other components involved in the readers. “There are hundreds of other components that depend on the display in some way, such as the drivers and microprocessors. Even though these are not directly part of the display we are working with the semiconductor manufacturers to improve these and reduce the component count. Moving to a system on a chip solution for e-book displays improves the performance, reduces the cost and enables animations to be shown on the display,” he said. To that end, E Ink has formed partnerships with semiconductor companies such as Epson, Texas Instruments, Freescale, Marvell and Maxim to jointly develop state-of-the-art integrated circuits that are a fraction of the cost of previous solutions.

Improvements in backplane electronics could also benefit these displays in future. Currently, each pixel of an E Ink display is made up of dozens of microcapsules; the resolution is limited by the backplane electronics. If the electronics could control each microcapsule individually, much greater resolution would be possible.

The impact of E Ink’s displays is reflected in the growth of the company. A year and a half ago, E Ink had about 100 employees and now it employs more than 250. It has maintained its roots, though; its head office is just down the street from MIT. The core microcapsules are manufactured in Massachusetts, and some of the coating for its roll-to-roll manufacturing process is done there. However, some coating and some of the more labour-intensive steps are now done in Taiwan, Japan and China.

Peruvemba is excited about the environmental benefits of the shift to e-books. “The paper industry is the second biggest generator of waste water,” he said. “And if you switch to electronic books you could save up to 300 trees depending on how much you read.”

He added that there is considerable interest in this technology from the developing world. “An e-book reader typically holds 1,000 books. Even if there’s only one e-reader in a class of children that’s a whole library. It could be the biggest market for displays and it’s happening already.”

Siân Harris is a science and technology journalist based in the United Kingdom.
**PICCO PROJECTORS**

**Interactive experience**

Adrian Cable

Holographic laser projection technology, combined with infrared touch-recognition technology, enables consumers to interact with a virtual display that can be projected onto a wall or table.

Consumers want smaller and smaller hand-held electronic devices, such as smartphones and PDAs, but they also want them to be able to display high-resolution multimedia content. This poses a challenge: such content, be it a video, photo, webpage or presentation, ideally requires a much larger display than the device can support — typically just 2.5-inch to 3.5-inch diagonal in size. The recent influx of ‘pico projectors’ to the market aims to address this. These miniature projectors connect to a host device such as a mobile phone or media player and allow consumers to project the content onto a wall or table so that it can be viewed and shared more easily.

The first pico projectors appeared in late 2008, and now some 80 brands are on the market, using a variety of projection technologies. These include liquid-crystal-on-silicon (LCOS) microdisplays based on light-emitting diodes; digital light processing (DLP) systems, which exploit a chip containing an array of microelectromechanical mirrors; and, more recently, laser beam steering (LBS) systems. LCOS and DLP systems form a miniature image on a chip that is then projected, whereas LBS systems direct one or more laser beams at a mirror that is rapidly moved to sweep or ‘scan’ the laser beam across the projection surface to form an image.

The potential impact of pico projectors is significant. Market analysts at DisplaySearch valued the revenues of this emerging sector at US$117 million for 2009 and predict it to rise to over US$13 billion by 2018.

However, in the two years since these small projectors were first launched, a significant change has occurred in the way consumers engage with content.

Viewing content is no longer a passive experience for consumers. With the rise of social networking, the smartphone, tablet computing and the application ecosystem, consumers increasingly expect to engage and interact with their multimedia content.
A typical imaging projection system works by displaying the desired image on a microdisplay, which is usually sequentially illuminated by red, green and blue light to form a greater range of colours. The microdisplay simply acts to selectively block (or amplitude-modulate) the incident light; after passing through magnification optics, the projected image appears. Conversely, holographic laser projection forms the image by illuminating a diffraction (or hologram) pattern with laser light. The image formed in the focal plane of the lens is related to the hologram pattern by a discrete Fourier transform.

The key task in a holographic projection system is to compute the hologram that is needed to create the image. A reasonable first guess might be to calculate the inverse Fourier transform of the image to obtain the desired result. However, the result of this calculation would be fully complex and no known liquid-crystal material can independently and continuously modulate both the amplitude and the phase of a light field. Even if such a material became available, the result contains amplitude components that would absorb incident light and reduce system efficiency. A much better approach, and the key to the efficiency advantage of HLPs, is to restrict the hologram to a set of phase-only values. As a result, when the hologram patterns are displayed on a phase-modulating microdisplay and subsequently illuminated, no light is blocked.

Light Blue Optics’ system uses a tiny, custom-manufactured ferroelectric LCOS microdisplay to display the hologram patterns. This requires that the hologram phase be quantized to a set of binary values, which introduces quantization noise into the resultant image. Such noise must be mitigated to maintain high image quality. This can be achieved by using the microdisplay to display $N$ independent holograms per video frame within the 40 ms temporal bandwidth of the eye. Each hologram produces a subframe with quantization noise statistically independent of the others (the time average is noise-free).

The key to Light Blue Optics’ HLP technology lies not only in the optical design but also in the algorithms used to calculate the phase hologram from the desired image. Light Blue Optics has developed and patented proprietary algorithms for the purposes of calculating $N$ sets of holograms per video frame both efficiently and in real time. Crucially, such algorithms can be efficiently implemented on a custom silicon chip, enabling high-quality video to be rendered effectively in real time.

create a native throw angle greater than 90°, enabling a 10-inch diagonal image to be created from a height of just 12 cm, which is roughly the height of a small mobile device standing on a table.

Another advantage is that lasers have a very wide colour gamut, meaning that colours appear incredibly rich and vivid. However, unlike LBS systems, which have a class 2 or higher laser safety classification, HLP products have a class 1 classification and are therefore completely eye-safe, which is essential for consumer electronics applications. Owing to the principles of Fourier optics, the image is always in focus, regardless of the distance between the projector and projected surface. An image can be projected onto the surface of the table with both the top and the bottom of the image being in focus at the same time despite being different distances from the projector aperture. Light Touch uses diffraction to form images, leading to bright images and low power consumption.

In addition, because the diffraction patterns of the image are calculated in software, any aberrations or distortions in the image can also be corrected and compensated for by the software, which simplifies the optical design. This enables the Light Touch projector to correct in software for the distortion inherent in the table-down projection geometry and produce a perfectly rectangular image on the table surface.

In Light Touch, we integrate the optical projection engine with infrared touch-sensing technology that forms a fan of low-intensity infrared laser light just above the projection surface. When the fan is broken by one or more fingers touching the table, a camera decodes scatter from the fan to deduce the location of the touch events (which may be single- or multitouch).

Light Touch works best with a flat surface such as a wall or a table for the touch functionality to operate correctly. Brightness is optimized when the projection surface is white. As with any other projection technology, projection is optimized when performed indoors and away from strong daylight.

As HLP steers light to where it is required and away from where it is not, the brightness of a HLP device is variable and depends on the nature of the content projected. Although it may seem that there is a lot of light in a movie or music video, such content has a typical image coverage of approximately only 18% in terms of area. When this type of content is shown on a first-generation Light Touch unit, it produces approximately 18 lm — marginally brighter than the DLP and LBS pico projectors on the market at present. When a control panel or ordering system (typically with 8% coverage) is shown on Light Touch, the brightness increases to 35 lm or more.

The whole Light Touch system — including the projection engine, the media processor and the operating system — consumes 6 W of power, giving a battery life of 2 h and comparing well with most pico projectors on the market.

Despite being restricted to indoor usage, an interactive projector such as Light Touch is capable of bringing a multimedia experience to a range of environments that conventional display technologies have found difficult to reach. Because the virtual touch-screen is projected, it is spill proof, fingerprint resistant and as easy to clean as an ordinary table top. In addition, when the projector is not in operation the display completely disappears. Applications that benefit from a virtual display include interactive ordering systems on tables in restaurants, bars and hotels, and wipe-clean, pathogen-resistant touch displays in healthcare environments. In the home, such a display could allow a wireless-network-enabled virtual touch-screen on the kitchen work surface for watching cooking programmes, browsing recipes and buying groceries online.

Light Touch currently has an HLP optical engine that is just 30 cm$^3$ in volume — roughly the size of a matchbox — but the technology is ideally suited to further miniaturization. The second generation of HLP engines, scheduled for release in 2012, will be less than 8 cm$^3$ in volume. Their optical architecture will deliver three times the brightness of a typical tablet screen for half the power. This second generation of tiny HLP projection engines will have the potential to become ubiquitously and seamlessly embedded in hand-held devices, homes, workplaces, retail spaces and even cars, fundamentally changing the way we see and interact with multimedia content.

Adrian Cable is Chief Technical Officer at Light Blue Optics, Platinum Building, St John’s Innovation Park, Cowley Road, Cambridge CB4 0WS, UK.

e-mail: office@lightblueoptics.com
**Microdisplays**

**Liquid crystal on silicon**

David Vettese

Microdisplays based on liquid-crystal-on-silicon technology may soon gain wider recognition as they penetrate an increasing number of markets, ranging from electronic viewfinders to miniature data projectors and head-up displays.

When it comes to display technologies, the concepts of both liquid-crystal displays (LCDs) and cathode ray tubes (CRTs) are widely known. The same cannot be said of liquid crystal on silicon (LCOS), even though this technology is used extensively in many industries that require high-quality microdisplays.

Most LCOS devices comprise a layer of liquid crystal sandwiched between a top sheet of glass coated with a transparent electrode, and a pixelated silicon substrate (or backplane) made by the complementary metal–oxide–semiconductor (CMOS) fabrication process. Because the silicon is reflective, it serves as a mirror element for each pixel, with the strength of the reflection electronically controlled by the amount of light transmitted through the liquid crystal above. Separate channels of red, green and blue light illuminate the LCOS chip in turn, with electronic drive signals controlling the transmission state of each pixel to form an active-matrix colour image. In some cases, a dedicated LCOS chip is used for each colour channel. This is a very simple and elegant design concept: the backplane is formed from a standard CMOS processed wafer and the glass substrate has no patterning. Indeed, the CMOS industry benefits from the heavy investments made by other industries, which allows for increases in pixel density (and, thus, higher resolution) without the need for LCOS manufacturers’ investment.

The origins of LCOS technology can be traced back to 1973, when Hughes Aircraft, of the USA, developed the first ‘discrete-element reflective display’, which was 1 inch in diagonal size. Hughes continued to be innovators in the field and in 1983 reported a ‘liquid-crystal light valve’, which was the first reflective spatial light modulator. Five years later, an LCOS spatial light modulator was reported at the University of Edinburgh, UK, with a resolution of 50 × 50 pixels.

It was not until 1993 that DisplayTech, of Colorado, USA (now Micron), reported a microdisplay of a resolution sufficient for use as a display. This 254 × 254 pixel array was capable of full red–green–blue image generation. The colour generation technique used in this display, the field-sequential colour system (images of each colour channel are generated separately in turn at a high rate and the human vision system interprets them as a single, full-colour image), was enabled by the use of a ferroelectric, fast-switching, liquid crystal. This has remained the main feature distinguishing the products developed by DisplayTech to this day.

In parallel, during the second half of the 1980s and the early 1990s, intellectual property in ferroelectric LCDs was developed by two UK research-and-development labs: Thorn EMI Central Research Laboratories and BNR Europe. This was subsequently combined with the electronic design skills of Admit Design, based near Edinburgh, UK, to spawn another LCOS company, MicroPix, in 1998. The focus of this development was to create a high-resolution LCOS device positioned to serve the rear-projection television (RPTV) market. MicroPix, now know as Forth Dimension Displays (ForthDD; www.forthdd.com), shipped its first SXGA-resolution microdisplay (1,280 × 1,024 pixels) in 2002 and this microdisplay is still in production today.

The RPTV market was initially heralded as a viable and commercially attractive option for high-definition televisions with large screens (that is, diagonal size greater than 32 inch) and vertical resolutions of 720 or 1,080 pixels. Manufacturing costs of large-panel LCD technology in the first few years of the twenty-first century were high in comparison with standard costs today. This enabled investment in the lower-cost, microdisplay-based RPTV concept and the related component suppliers to that industry, particularly the microdisplay manufacturers.

This investment allowed microdisplay technology to mature, and three categories of microdisplay for projection emerged. These were LCOS (through many manufacturers), 3LCD (featuring three transmissive micro-LCDs, from Epson and Sony) and microelectromechanical systems (MEMS, predominantly based on the Texas Instruments digital micromirror device). However, large-panel LCD technology, specifically their manufacture, also quickly matured and it became apparent that large-panel LCDs were to be a more popular consumer choice, despite leading market analysts stating that better image quality could be achieved on an LCOS-based RPTV set. By the end of 2007, nearly all microdisplay RPTV manufacturers had withdrawn their televisions.

This left a challenge for microdisplay manufacturers. A number of companies simply disappeared, as they did not have alternative revenue streams, or became occupied by other technologies. Some companies were able to survive by diversifying, for example by supplying business solutions and home cinema projectors. Others, such as ForthDD, chose a more niche-market route, supporting and focusing on professional and high-end application spaces.

Of the application spaces that ForthDD focused on, the main market was again a display market. Although technologies such as Texas Instruments’ digital light processing can produce higher brightness,
LCOS is a smaller, more flexible platform and can give very high performance in small spaces. This makes LCOS ideal for applications such as near-to-eye (NTE) displays for viewfinders, head-mounted displays and, recently, picoprojectors — miniature digital projectors designed to connect to portable electronic devices.

The high performance of these applications arises from the fact that an LCOS display is based on a reflective CMOS with an unpatterned glass cover. The pixel circuitry is behind the face of the pixel and, therefore, completely out of the optical pathway. This allows for extremely high image fill factor and for the spaces between the pixels to be so small that they are negligible. In contrast, an LCD has the pixel circuitry within the optical pathway and this blocks some of the light, causing the ‘chicken wire effect’ that occurs when a projection is viewed through a transmissive panel. Another alternative technology, organic LED microdisplays, involves subpixels that are each about 25% of the area of the pixel face. This means that although in an LCOS display about 95% of the pixel can be used to generate the separate colours, in an organic LED this figure is only 23%. When seen in an NTE display, the effect is quite striking and very distracting.

The LCOS microdisplay can also achieve a wider colour gamut than fixed-colour-gamut microdisplays because LCOS uses separate illumination sources for each colour channel. This allows ‘scene-adjustable’ and aesthetically accurate colour reproduction (without quality-reducing pixelation) to be achieved successfully in an NTE microdisplay package based on an LCOS microdisplay (Box 1).

These image quality differentiators are particularly relevant to the professional NTE applications. LCOS microdisplays are used, for example, in weapons sight and periscope simulators for military training, in binocular imagers for microscope simulation for medical training, in head-mounted displays for pilot-training and mission rehearsal, and in electronic viewfinders for cinematography applications.

In the military and medical training space, the accuracy of a simulated image is paramount and this replication of reality is a much sought-after feature. This verisimilitude is essentially driven by the display resolution as well as the aforementioned image differentiators. Microdisplay resolutions can vary from the very lowest, QVGA (320 × 240 pixels), standard up to about the 4K standard (4,000 × 2,000 pixels). Since 2002, the SXGA-resolution microdisplay from ForthDD has been widely used in military NTE applications and has been designed into many training systems. A good example is in missile launcher training, which can now be achieved to the same degree of accuracy and effectiveness in synthetic environments as it can in live training environments. Although there is unlikely to be a complete move away from live training in favour of the synthetic equivalent, increasing use will have an effect on overall training costs and time-to-combat readiness.

Recent developments in cinematography have also had a direct impact in increasing the use of LCOS technology. The recent and ongoing move from the recording of movies on 35 mm film to a fully digital recording solution has seen a need to change from the traditional viewfinder technology in cinema cameras, namely an optical viewfinder, to an advanced LCOS solution in an electronic viewfinder.

The design brief for this was exceptionally difficult: replicate the image quality achieved with an optical viewfinder in an electronic manner. The optical viewfinder has near-infinite resolution, a 100% fill factor, no flicker and no image

---

**Box 1 | Illumination options**

A range of illumination sources have been used in conjunction with microdisplays. Lamps are generally used for larger-sized, higher-brightness applications, such as projectors and RPTVs. LEDs have widespread application, from lower-illumination applications such as NTE displays to some scientific equipment such as confocal and interferometer microscopes. Increasingly, LEDs are also being used in compact projection applications.

Red, green and blue lasers are now finding their place too. Some pico projectors have laser illumination, such as the scanning-mirror type from Microvision or those from Light Blue Optics that use their extremely clever Holographic Laser Projection technology. However, there are some supply-chain issues relating to the availability and price of the lasers, which are holding back the diffusion of this particular illumination innovation.

The choice of illumination source affects the colour gamut of the displays. With lamps, to achieve colour the illumination has to pass through colour filters, for example a rotating colour wheel. The gamut achievable with this is relatively low in comparison with the other illumination methods. This is also true of microdisplays that use colour subpixels, which are essentially colour filters next to the optical pathway.

LEDs have an excellent colour gamut and can achieve well in excess of the ITU-R Recommendation BT.709 colour gamut (for high-definition television) on the CIE 1931 chart, and come close to the NTSC gamut. We believe that lasers can improve on this.

The brightness that can be achieved with LCOS displays ranges from about 14 lumens for pico projectors to many thousands of lumens for home cinema and digital cinema applications.
artefacts — in other words, it is a true representation of what the human visual system sees. It is purely a glass magnifier that views the image captured through a cinematographer’s lens. To replicate this with a microdisplay solution in an electronic viewfinder would be impossible. However, LCOS image quality closely approximates this with a high resolution of $1,280 \times 1,024$ pixels, an accurate colour gamut and no noticeable pixelation or flicker.

There is another product in development that could bring the acronym LCOS to consumers around the world. This application is pico projection, where an extremely small digital image projector is integrated with or connected to consumer hand-held devices such as PDAs or mobile phones.

To meet this need, microdisplays are evolving and becoming smaller as pixel size decreases (again leveraging the CMOS manufacturing industry) and resolution decreases so that the projector can be made sufficiently small. Today these microdisplays are typically between about 0.2 and 0.9 inch in diagonal size and LCOS pixels vary from about 6 to 13.7 $\mu$m in size. Future pico projectors may be less than 0.2 inch in diameter, with pixels less than 6 $\mu$m in size. Display resolutions will also need to be reduced to WVGA ($800 \times 480$ pixels) to fit whole projectors into small, unobtrusive packages.

Image-sharing will be enabled by projection from mobile phones and other media players, whereas previously images could only be viewed on small, hand-sized, LCDs. This will result in the manufacture of microdisplays in unprecedented volumes, with market estimates suggesting volumes greater than 100 million per annum. A number of large manufacturers of electronic components are positioning their product line cards to include an LCOS solution in preparation for the day when the technology is adopted by a gadget- and technology-savvy public.

LCOS technology has been around in various guises for many years and is now verging on mass-market adoption. It is inevitable that LCOS will become a household acronym to sit alongside CRT and LCD. But at the same time, LCOS will continue quietly serving a number of high-end markets in military, medical and cinematography applications. All these require the best in image quality and they all use LCOS technology.

David Vettese is European Sales Manager at Forth Dimension Displays, 7 St David’s Drive, St David’s Business Park, Dalgety Bay KY11 9NB, UK. e-mail: dvettese@forthdd.com
Multistring backlight drivers aid power management

US analog semiconductor manufacturer Advanced Analogic Technologies has developed a range of multistring LED backlight drivers for 10- to 22-inch LCD panels. The AAT1409/7/5 products offer integrated boost converters and precision current sinks that can support up to 88 LEDs at a total current of 360 mA. The drivers also reduce the number of backlight printed circuit boards required while still driving high-brightness LEDs and controlling the backlight intensity, thus ensuring uniformity across the display.

“As LCDs continue to gain traction in the computing, consumer and industrial markets, the power, efficiency, accuracy and flexibility of the backlight drivers are becoming critical differentiators,” says Ray Chan, technical marketing manager at Advanced Analogic Technologies. “These products offer an effective approach for LCD power management.” The drivers can operate from d.c. inputs, cigarette lighter adapters or multicell lithium-ion batteries in the range of 4.5–26 V, and are available in four, six or eight channels. The drivers also support a pulsewidth modulation dimming frequency of up to 100 kHz, which ensures silent operation. Furthermore, these drivers are particularly suited for use in portable LCD devices operating under low ambient light conditions or in power-saving modes, as their high efficiency allows the battery life to be maximized.

www.analogictech.com

Glass bonding boosts display performance in bright light

Hitachi Display Products — the arm of Hitachi Europe responsible for LCD development — has developed a glass bonding technique that enhances the optical performance of LCDs in bright ambient light. An optical adhesive and lamination process is used to bond an anti-glare and anti-brightness glass substrate to the front of a thin-film transistor (TFT) LCD module. When used in bright light, the amount of ambient light reflected by most displays is close to or exceeds the light emitted by the display, leaving the image “washed out.” But according to Mark Stephenson, product marketing manager at Hitachi Display Products, a TFT LCD featuring surface treatment techniques and an optically bonded glass substrate can reduce reflections to less than 0.2% by scattering and absorbing ambient light. As Stephenson also points out, the bonding process doesn’t leave an air gap between the glass substrate and the display, which prevents parallax effects and internal reflections. “The display module is more rugged than traditional TFT LCDs, thus providing enhanced shock and vibration performance,” he adds. “Display durability is also improved with increased impact and scratch resistance, and reduced fluid and foreign ingress.”

www.hitachi-displays-eu.com

White LED targets outdoor displays

US components manufacturer Vishay Intertechnology has developed a non-diffused 3 mm white LED that uses InGaN technology to achieve a luminous intensity of 4,500–11,250 mcd at 20 mA. Featuring a clear, untinted plastic case with a lens viewing angle of ±22.5° and high light output, the VLHW4100 provides an alternative to incandescent lamps in outdoor LED panels, light guides and other applications. The LED also provides thermal resistance down to 400 K W⁻¹ and power dissipation up to 95 mW. Withstanding electrostatic discharges up to 2 kV, in accordance with JEDEC standard JESD22-A114-B, the device is compliant to the restriction of hazardous substances directive 2002/95/EC.

www.vishay.com

Fully de-speckled laser system targets digital cinema

Laser Light Engines, a US manufacturer of laser-driven light sources, has developed a fully de-speckled laser illumination system for digital cinema and large-venue projectors. Producing red, green and blue from the same laser, the system completely eliminates laser speckle in images, reaching the level of performance required for digital 2D and 3D films. “Our lasers will also reduce power consumption and cooling costs, thus providing a cost-effective and environmentally friendly alternative to xenon arc lamps,” says Bill Beck, executive vice president of business development at Laser Light Engines. “And unlike these lamps, the system will provide full brightness over the lifetime of the projector.”

www.laserlightengines.com

PHOLED system boosts display performance

US firm Universal Display has developed a light-blue phosphorescent organic light-emitting diode (PHOLED) emitter system that could significantly reduce the power consumption and extend the lifetime of OLED displays, thus benefiting the battery life of portable electronics. Under accelerated test conditions, the system generated for 9,000 hours to 50% of its initial luminance of 1,000 cd m⁻² — an increase in operating lifetime of almost 100% over the company’s previous light-blue PHOLED emitter system. The system offers CIE chromaticity coordinates of (0.17, 0.37) and a peak wavelength of 472 nm. It also provides a luminous efficiency of more than 45 cd A⁻¹, which corresponds to an external quantum efficiency of more than 20% at 1,000 cd m⁻². The company developed the all-phosphorescent active-matrix OLED architecture by adding a light-blue subpixel to the conventional red–green–blue configuration. The company has already demonstrated the architecture in a 2.5-inch, all-phosphorescent active-matrix OLED display.

www.universaldisplay.com

Transparent OLED makes its debut

Japanese manufacturer TDK has announced two types of passive-matrix organic light-emitting diode (PM-OLED) displays — one flexible and the other highly transparent. The 3.5-inch flexible type is based on a resin substrate, has a thickness of only 0.3 mm, weights 1.11 g and has a resolution of 256 × 64 pixels. It is available in either colour or monochrome models. The transparent PM-OLED, which is primarily targeted towards the mobile phone market, has a light transmission of 50% and comes with a 2-inch screen at QVGA resolution (320 × 240 pixels). Mass-production of the flexible PM-OLED is expected to start before the end of 2011, with the transparent type available for sampling immediately.

www.tdk.co.jp
Watch this space

Munisamy Anandan, president of the Society for Information Display, talks to Rebecca Pool about the breath-taking technologies that are now emerging in the displays market.

Which display technologies are we likely to see more of in the near future?
There has been a lot of recent excitement regarding three-dimensional (3D) video. The 3D television market had sold out completely after launch, despite the current economic downturn. Panasonic expects to sell one million units this year, while Samsung is expecting to sell nearly two million units.

Vigorous research is underway to eliminate the need for 3D glasses, although it may take another three or four years to reach a stage where people can view a 3D television without glasses. There are glasses-free prototypes that exhibit a 3D effect if the user stands directly in front of the screen, but this is lost if the user stands anywhere else.

Today’s customers also want touch-screens that have the touch-sensitive element inside the display rather than on the top. This is particularly the case for applications such as smart phones; researchers are now working on a technology called ‘in-cell touch’, in which sensors are built into every pixel of a liquid-crystal display, making the final device thinner, brighter and more lightweight.

Has any particular technology been crucial to the growth of the displays markets over the past decade?
Yes — the LED backlight. We first saw it in mobile phones, and now LCD notebooks are almost completely illuminated by LED backlights. The technology has, at least over the past five years, started to dominate LCD televisions, which demonstrates phenomenal growth. Power consumption has come down, and the longevity of these devices has increased tremendously as a result.

The electronic book (e-book) will be the next big growth market for the LED backlight. A few years ago many people doubted the potential of the e-book market, but only recently Amazon.com saw sales of e-books surpass those of hardback books for the first time. My guess is that this will happen globally over the next three to four years.

Are there any other technologies to look out for?
One technology waiting to challenge the LCD is the organic LED (OLED). Unlike LCDs, OLED displays do not require a backlight to function, and so are very thin and lightweight.

However, at present, manufacturers cannot economically manufacture OLED screens larger than 15 inches. The backplanes of these displays contain low-temperature polysilicon thin-film transistors (TFTs), which do not exhibit uniform characteristics over a large display area. Also, the manufacturing cost of these transistors is high, but yields are low.

A new generation of TFT — the oxide TFT — looks promising. Indium gallium zinc oxide TFTs, for example, not only exhibit good performance characteristics over a large display area, but also can be manufactured in fewer processing steps than polysilicon TFTs.

Unfortunately, these performance characteristics can deteriorate after exposure to moisture and oxygen during the fabrication process. When researchers solve this problem, manufacturers will be able to scale OLED screen sizes to 32 inches and beyond while implementing economical mass-manufacturing processes. The performance of oxide TFTs has already been demonstrated at the recent Society for Information Display international symposium in Seattle, USA, so we should see them in manufacturing lines over the next two to three years.

Researchers have also explored using OLED displays in e-books. Although this technology has a wider viewing angle and superior colour quality compared with an LCD, its power consumption is higher than that of an LCD and backlight combined. This is a major problem for e-books, as end users do not want to charge their devices frequently.

An alternative would be to use phosphorescent OLEDs, which are three times more efficient than standard OLEDs and could therefore drastically reduce the power consumption of e-books if they can be economically mass-manufactured.

Where are the opportunities right now?
Many multinational display companies are looking to invest in China, particularly to establish LCD manufacturing plants. Making the LED backlights for LCDs requires the LED manufacturing infrastructure to be in place, so China is now vigorously trying to establish extensive LED manufacturing operations. The government is subsidising critical manufacturing equipment, including nearly 50% of the cost of an embossing tool.

China has been doing the back-end packaging of LEDs for a long time, but now it wants to manufacture the LED chips themselves.

As president of the Society for Information Display, what are your plans for the future?
We would like to develop our partnerships with various countries. For example, we already have partnerships with France, Korea and Japan, and we wish to strengthen such links. Some companies are unaware of the strengths of certain universities around the world, so we are trying to provide information on the technological strengths of each university, where the breakthroughs are coming from, and how industry could benefit from interacting with these universities. For example, I am trying to establish a database in which we will compile all the universities in the world and categorize them based on which field of technology they are strongest. This type of information will be highly useful for industry and will help display technologies to grow. We are also increasing our activities on the internet. Many of our members operate remotely nowadays, so we want them to be able to watch or listen to seminars online. The migration of display technologies to China and also to Brazil will allow us to increase our membership in these countries, organize more conferences and partner with more local societies. This is in tune with our mission: to promote display technologies around the world.

INTERVIEW BY REBECCA POOL

Rebecca Pool is a freelance journalist based in the United Kingdom.
**THIS WEEK**

*Nature* is the pinnacle journal publishing *opinionated editorials* coupled with *hard hitting views* by global experts discussing the *most important scientific issues* in world view. *This week* equips you with a succinct round up of highlights and timely news.

**NEWS IN FOCUS**

*Nature* publishes *in depth analysis* of the most important science policy, business, community and breaking news written from an *international perspective*, whilst giving you an *inside advantage* on the new ideas, approaches and challenges to research.

**COMMENT**

*Nature* boasts the *largest and most comprehensive* Books & Arts section among all science journals. Publishing comments written by *world authorities* and continuing debate on material published in *Nature*, our authoritative *expert opinion* on any issue resonates beyond any one field of research.

**CAREERS**

Whether explicitly or implicitly, the *Nature* careers section offers you *advice* and points you to *actions* pursuing *success*. More than a list of pointers, each piece will focus on a *unique niche* such as new grants, programs, and industry trends.

---

Nature.com/rediscover

© 2010 Macmillan Publishers Limited. All rights reserved
Recommend to your librarian

With online access your institution can provide you with:

24-hour desktop access to:
- Articles online ahead of print (Advance online publication)
- Searchable online archive
- Reference linking within and beyond NPG
- “Export Citation” and “Export References”
- “See more articles like this” and “Related links”

To access this latest photonics research online, recommend site license access to your librarian

www.nature.com/naturephotonics