MICRODISPLAY ISSUE

Information DISPLAY

July 2000
Vol. 16, No. 7

SID

Official Monthly Publication of the Society for Information Display

- *Microdisplay Overview*
- *LCoS Technology and Applications*
- *Making LCoS Microdisplays*
- *Integrated Flexible LCDs*
- *IDMC Preview*

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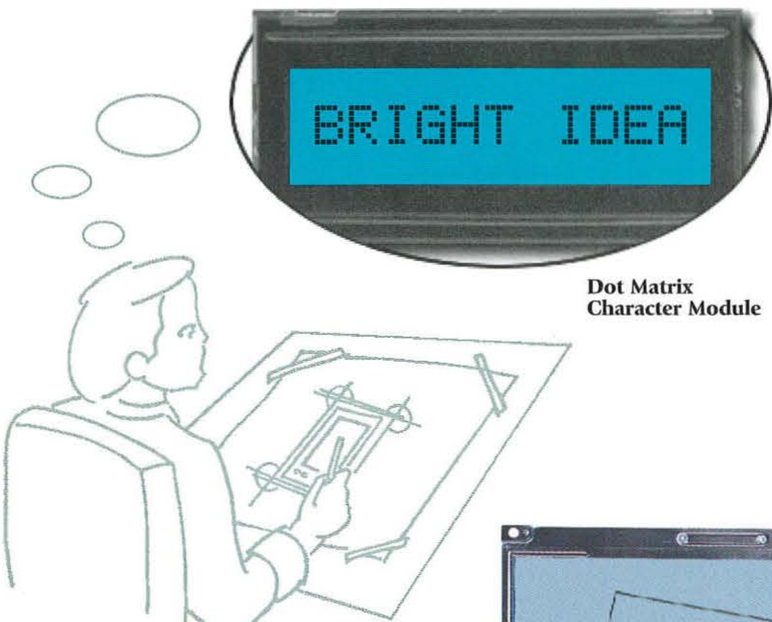

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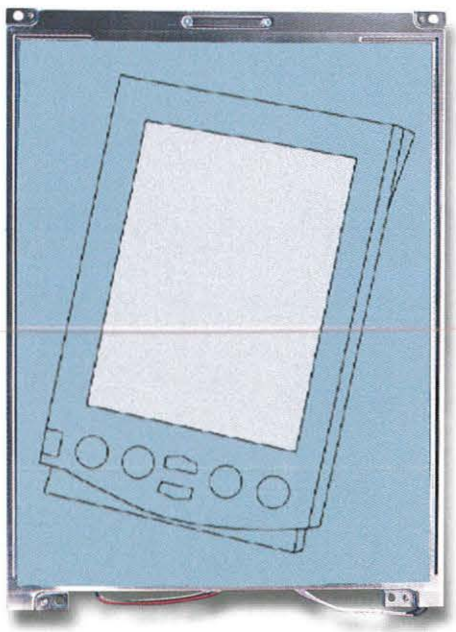

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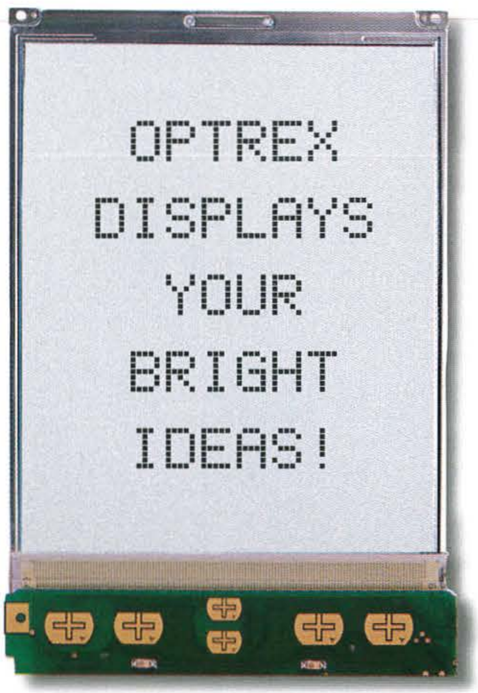

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Circle no. 1

Information DISPLAY

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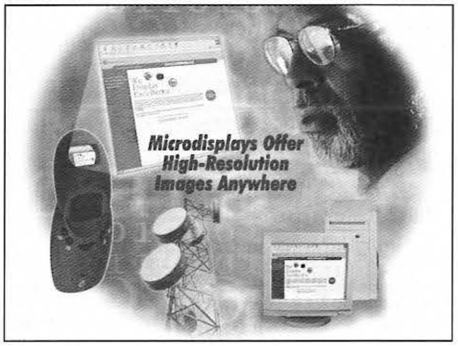
COVER: As a rule, our high-resolution displays stay on our desks or live inside our semi-portable notebook computers. But when we really travel light – with only a cellular phone and PDA to fight off the dark forces of non-instantaneous communication, disorganization, and information overload – we travel with low-information-content displays. The combination of microdisplays and high-bandwidth wireless networks can end that, and put graphic-intensive communications and information services in our shirt pockets and purses. And that accounts for a lot of the excitement in the microdisplay community.



Three-Five Systems

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Next Month in
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Industry Directory Issue
- Directory of the Display Industry
- Lamps for Projection Displays
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- CeBIT 2000 Report

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editorial

Microdisplays Explode ... Slowly

This is *Information Display*'s second annual special microdisplay issue, and this year may be the year of the microdisplay. At least, it is the year in which liquid-crystal–on–silicon (LCoS) microdisplays will first appear in a variety of commercial products and product prototypes.

But nothing in the display world happens quickly. Microdisplay technology is exciting because it promises high-resolution display systems at low cost. Used as a "virtual display" for portable systems, it offers high-quality images from a small package that uses very little power. Used in projection systems, it offers large high-quality images for TV and desktop monitors at costs that could be substantially less than those of competing technologies.

So why isn't the microdisplay market exploding quickly rather than slowly? A major driver of high-resolution color displays in advanced cellular phones and other portable electronics will be the broad availability of high-bandwidth wireless connections to the Internet. They don't exist yet, although they're certainly coming. The current generation of wireless Net phones can only access limited text-based content at low speeds. High-resolution color displays (either virtual or direct-view) are not needed for this application, and they would drive phone prices out of the current competitive range without offering the user commensurate value. So, for this application, microdisplays have to wait for the wireless infrastructure to provide the problem for which they are the solution. That will probably take another year (or two or three).

Another issue is that for microdisplays to be effective as virtual displays – displays that produce a perceived image much larger than the display's dimensions – they require a good optical system. Designing such a system with large eye-relief (the distance from the exit pupil of the optical system to the viewer's eye, so the viewer can view the image comfortably), large "eye box" (the volume of space in which the image can be seen), good optical resolution, flat image field, small physical depth, light weight, and low cost is a substantial optical-design challenge. Inviso has been regarded as having the prototype optics with the best performance, and Inviso prototypes have been impressively comfortable to use.

Product planners worry about whether virtual displays will have a high degree of user acceptability. If production optics with the quality of Inviso's prototypes can be made at reasonable cost, acceptability could be quite high. If manufacturers try to cut corners on the ergonomics and image quality of their optical systems, they could kill the goose before it has a chance to lay any golden eggs.

Microdisplays appear to be well suited to rear-projection TV and desktop monitors. The problem is that the pundits are only predicting a market of 3–4 million rear-projection TV sets by 2005 and a somewhat smaller number (but higher value) of business projectors. Stanford Resources feels the lion's share of those rear-projection TV sets will still be CRT-based in 2005. Even if one is very optimistic about the microdisplay's penetration of these markets, the number of devices they will consume is not huge.

The volume market is in portable and personal viewing devices of various sorts, and many of those devices have not been created yet, or are waiting for an infrastructure to be put in place.

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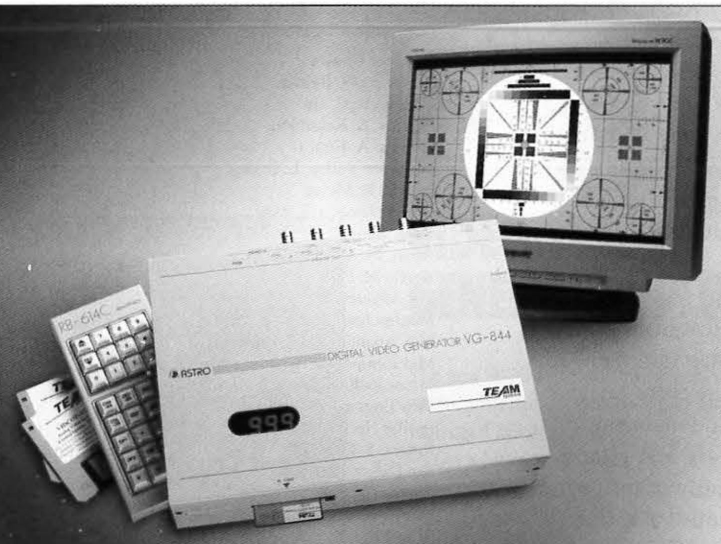

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a view from the hilltop

Are We Falling Behind? ...

by Aris Silzars

It was the middle of the afternoon on a bright sunny day at 39,000 feet somewhere over the North Pacific Ocean. Inside the passenger cabin of the spacious Boeing 777 – except for the emergency lighting, an occasional reading lamp, and the soft glow of several hundred LCD video screens – it was dark. All the window shades were tightly drawn, and the passengers were immersed in watching the video displays on the seat backs in front of them – or on the armrest extensions in business and first class. Not being a serious movie watcher, I raised my window shade a few inches to see out. The passenger across the aisle from me immediately complained that he couldn't see his movie. I fussed, but grudgingly complied and put my window shade back down.

I don't like sitting in the dark! I like to see daylight when it's available – bright sunlight especially. Nevertheless, I felt I should be considerate of my fellow travelers, closed my shade, and sat in the dark for the remainder of the nine-hour flight.

Having thus been politely chastised by a fellow passenger, and now being in a grumpy mood because I wasn't free to satisfy my own preferences, I began to analyze the situation. No question about it. The LCD panels in this latest version of the "triple-seven" were just barely adequate even for this non-critical captive-entertainment application. This led me to recall an article that I had seen just a few days earlier in *USA Today* about the new portable devices that are aiding the evolution of the interconnected society. In this article by Kevin Maney entitled "Wireless Option Opens Door to a New e-World," the passage that caught my eye said, "There are caveats. Actually, lots of them. ***The screens stink***. The access is slow. The offerings are meager. ***You have to work your way through menu hell to find things***." (Bold emphasis added.) As a longtime member of the display community, those words cut pretty deep. Unfortunately, as I thought about it, I realized that in general I would have to agree with Mr. Maney's assessment that most portable devices do not have such great-looking displays.

Over the last two decades, the use of electronic displays in non-television applications has evolved from a few specialty products such as test instruments, military systems, and data terminals to become the primary human interface with computers and data-communications devices. In 1980, there were no desktop or laptop computers. Today, their computing power rivals the mainframes of only a few years ago. Communications has evolved from a few "car phones" to a state in which almost everyone is now reachable independently of his or her location. These changes were predicted by the well-known Moore's law that states that computing power approximately doubles every 18 months to two years. Some well-respected software types claim that image-processing capability is currently evolving even faster. The rate of data communications and database "interconnectedness" is also increasing rapidly.

This leads me to pose two important questions to those of us in the display community: "How are we doing in bringing exciting new display products to market?" "Is the rate of display development commensurate with progress in computing power, imaging software, and communications bandwidth availability?"

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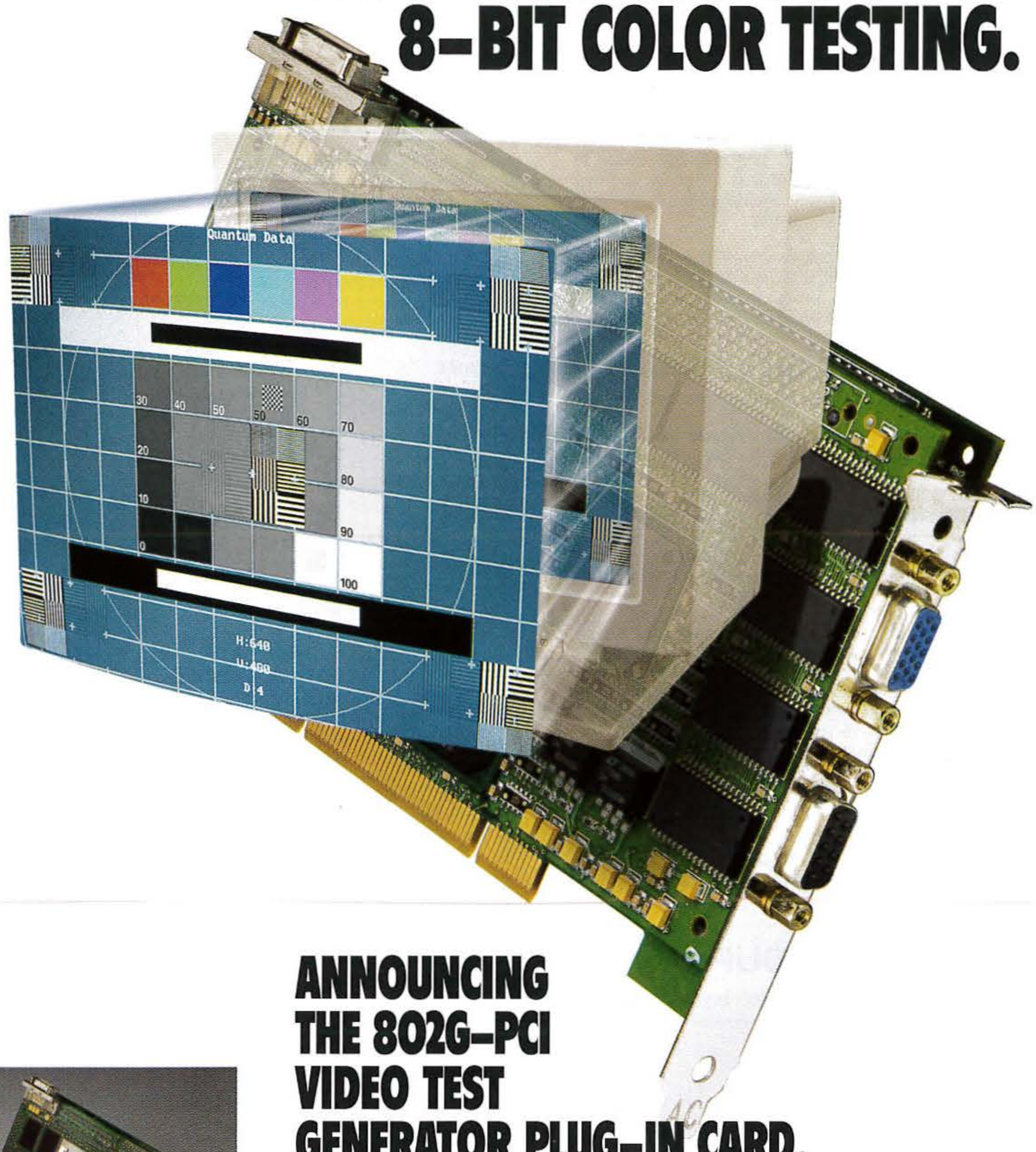

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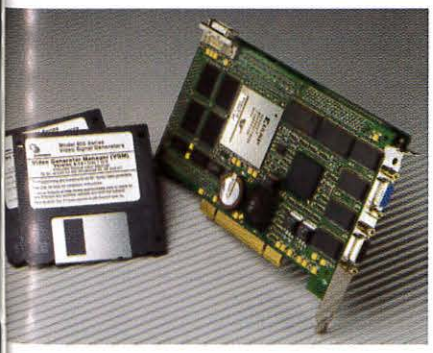

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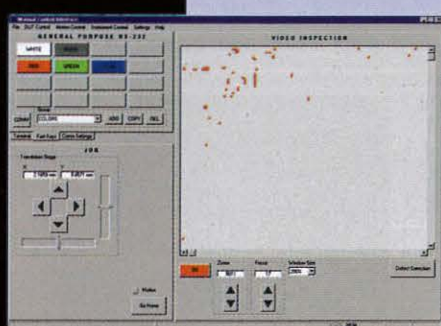

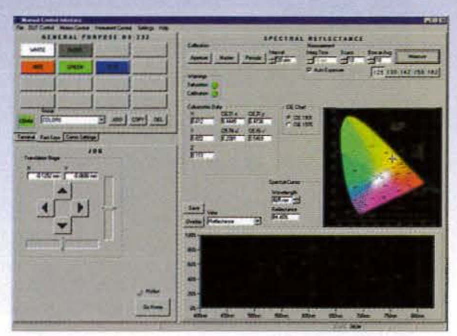

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Circle no. 9

The Technology Is Pushing – But Will the Market Pull?

Many microdisplay companies are producing impressive prototypes, and partnership announcements are popping up like spring crocuses. The sellers are clearly ready to sell – but will the buyers buy?

by Paul D. Semenza

THE BIG NEWS is small displays. Numerous companies are developing microdisplays as components and as systems. The door of opportunity has been left open by the limitations of traditional technologies; existing displays tend to get larger, heavier, and more expensive as image size and pixel count increase. The two most competitive features of microdisplay technology are the ability to display large numbers of pixels and to do so in a light-weight package that occupies a small volume.

These attributes are appealing for new products designed to take advantage of microdisplays, as well as replacement designs that can compete head to head with the existing, established technologies.

What Are Microdisplays?

As the name implies, microdisplays are very small displays that are typically viewed through the use of optics. While no formal definition exists for the size of a microdisplay, most in the industry would agree on a diagonal measurement of 1 in. or less.

High-density information displays currently have from 100,000 to more than 1 million pixels. Clearly, a 1-in. display with such pixel counts must be coupled to an optical system to create reasonable viewing conditions. There are two methods used to implement microdisplays. In personal viewers, an optical system is utilized to project a "virtual" image that appears to be much larger than it actually is; they are best suited for compact head-mounted or handheld devices. Projection systems are designed to magnify a small image onto a screen for viewing by one or more users.

Besides their very small size, the other key feature of most microdisplays is their fabrication upon silicon (or quartz) substrates rather than on glass, as are direct-view flat-panel displays (FPDs). This feature has led to production arrangements that are a departure from those typically seen in the display industry. Rather than requiring new investments in production facilities that use increasingly large glass substrates, microdisplays can be fabricated on existing semiconductor equipment, which leads to the possibility of flexible arrangements between display developers and semiconductor firms.

By building the display directly on semiconductor substrates, designers can integrate

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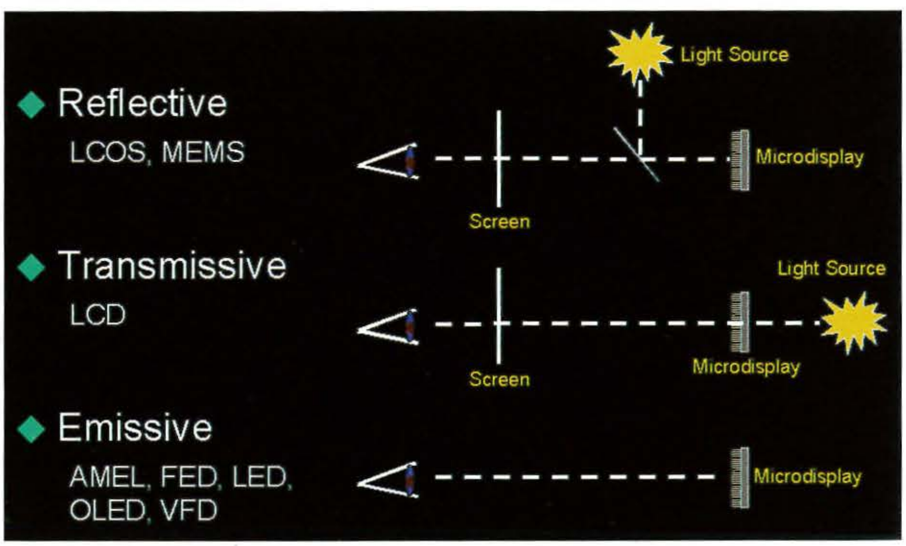

***Fig. 1:** Microdisplay technology can be divided into three categories.*

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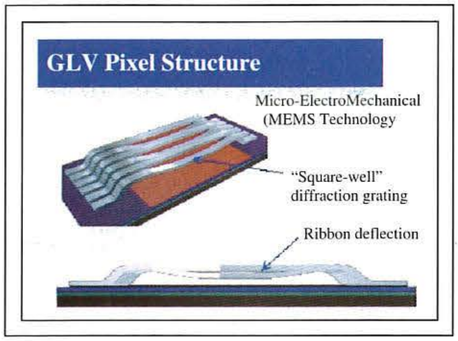


Silicon Light Machines

Fig. 2: *The Grating Light Valve™ (GLV™) technology deflects the ribbons of a diffraction grating to create a linear array of pixels for an image.*

electronic components – such as row and column drivers, digital and video interfaces, and control circuits – directly alongside the display on the same substrate. This can lead to higher performance at lower manufacturing costs.

Microdisplay Technologies

As with direct-view FPDs, there are three types of microdisplays: reflective, which modulate an external light source by varying the properties of a reflecting surface; transmissive, which modulate an external light source as it is transmitted through the device; and emissive, which produce light internally (Fig. 1).

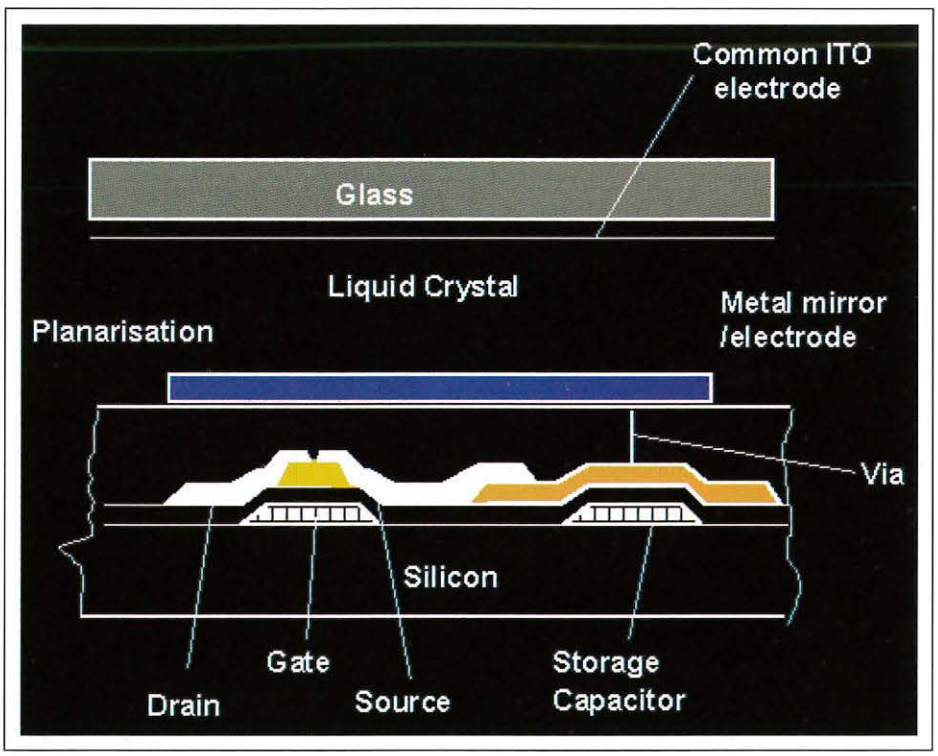
Reflective microdisplays. The two main types of reflective microdisplays are microelectromechanical systems (MEMS) and liquid-crystal on silicon (LCoS). MEMS devices use semiconductor-fabrication equipment and processes to build miniature systems that have both mechanical and electrical components. They rely on the physical movement of a display element (pixel or line) to modulate the amplitude or phase of an external light source. There are three types of MEMS microdisplays that have been demonstrated (although others are in development); of these, only the first is in production.

Texas Instruments developed and produces the Digital Micromirror Device™ (DMD™), which integrates discrete tilting mirror elements with complementary metal-oxide-semiconductor (CMOS) addressing circuits at each pixel location. The micromirrors are fabricated on hinges on top of a static RAM (SRAM) chip. Devices with 1024 × 768 pixels came on the market in 1998 and will be the most prevalent type of DMD in 2000; 1280 × 1024-pixel devices followed in 1999, but still account for less than 1% of the DMD chips.

DMD is a potential technology for HDTV projection systems; it is capable of producing projected images from all currently operational or proposed high-definition standards, and demonstration systems have been built with 1920 × 1080 pixels. Texas Instruments has developed a subsystem called a Digital Light Processing™ (DLP™) engine, which is sold to numerous projection-system vendors for use as the core of their systems. Configurations with one, two, or three DMD chips have been developed utilizing color wheels and/or dichroic (color-splitting) prisms.

The actuated mirror array (AMA) was developed by Aura Systems in the early 1990s. Daewoo Electronics licensed the technology and has been developing the concept further under the name thin-film micromirror array (TMA). The device is similar to the DMD in concept and system design, although the TMA uses an optical stop to determine gray level, whereas the larger rotation angles of the DMD allows the display to be coupled directly to the projection lens. DMD uses temporal dithering to create gray levels. TMA uses piezoelectric materials – instead of DMD's electrostatic forces – to tilt the mirrors. Piezoelectric materials constrict or expand in response to an applied voltage. Each mirror sits on a pair of piezoelectric posts, and when one post is constricted and the other expanded, the mirror tilts toward the constricted post. This allows gray levels to be produced directly.

The Grating Light Valve™ (GLV™), invented at Stanford University and developed by Silicon Light Machines, is a silicon-based integrated circuit with a micro-machine reflection phase grating (Fig. 2). A series of suspended silicon nitride beams – referred to as ribbons – are coated with a reflective aluminum layer. The parallel ribbons are approximately 3 μm wide, 100 μm long, and 100 nm thick. Each ribbon is supported at both ends and is suspended above an air gap of approximately 650 nm. When a potential difference is applied between the aluminum coating on a ribbon and a conductive layer below the air gap, the ribbon is pulled down by electrostatic force.



MicroPix

Fig. 3: *A liquid-crystal–on–silicon (LCoS) display is structured much like a typical active-matrix panel, but using a tiny silicon substrate instead of glass.*

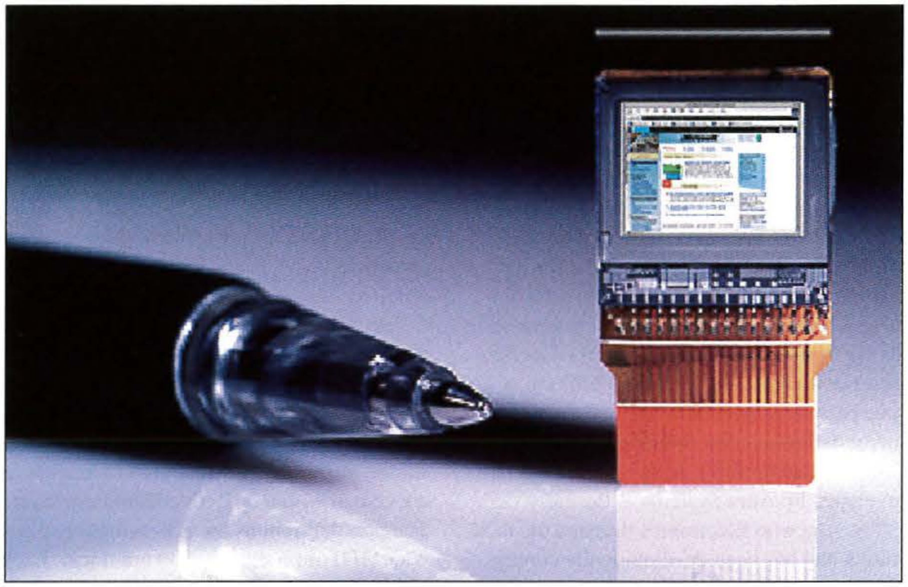


Fig. 4: Small reflective LCoS displays provide tiny high-resolution images.

This effect is very fast acting – as fast as a 20-nsec switching time.

A distinctive feature of a GLV projection system is that it consists of linear arrays of pixels, which are scanned perpendicular to the array to form an image. This is in contrast to the more typical two-dimensional pixel array. The fast switching time of the GLV allows information in the horizontal dimension to be presented through scanning. Silicon Light Machines has demonstrated a projection system using red, green, and blue laser sources. The primary colors illuminate three GLV arrays with 1080 pixels that are scanned with a galvanometric mirror to produce an image with 1920 × 1080 pixels.

LCoS microdisplays are similar to direct-view active-matrix liquid-crystal displays (AMLCDs) in that they utilize the light-modulating properties of liquid-crystal (LC) materials. In an AMLCD, the cell is made of two glass substrates containing a layer of LC material. Each pixel is controlled by a thin-film transistor (TFT) deposited on one of the glass layers.

LCoS displays substitute a silicon substrate for one of the glass sheets, and instead of TFTs on glass, LCoS displays use bulk-silicon devices to control the pixels from outside the optical path. The silicon-based CMOS substrate serves as both the active matrix and the reflective layer. The thin layer of LC, the glass plate, and the polarizer are then deposited on top (Fig. 3). Utilization of a single-crystal-silicon substrate and a thinner LC layer provides LCoS devices with much faster switching than the amorphous-silicon or polysilicon layers in AMLCD panels. LCoS devices also have a simplified LCD structure; the reflective substrate requires only one polarizing layer.

Two other phenomena are used to modulate light in LC microdisplays. Both use unpolarized light, which allows for much greater light transmission because polarizers absorb a large portion of transmitted light. In one approach, light is scattered when the LC molecules are arranged in one fashion and reflected when the molecules are rearranged, a process that is controlled by the application of a voltage across the cell. Scattering displays typically use polymer-dispersed LC (PDLC) materials.

The second approach uses the principle of diffraction: A periodic arrangement of ON or OFF pixels forms a grating, which causes light to constructively or destructively interfere. This interference pattern can then be filtered by a Schlieren stop to pass light when the pixel is in certain grating modes. By altering the grating structure, the amplitude and color may be controlled. Most diffractive systems use twisted-nematic LC material.

LCoS devices produce color images in several ways. The most popular approach for projection applications is to use three LCoS chips and dichroic mirrors to separate red, green, and blue components. Another choice uses a color-filter wheel to present field-sequential color to a single chip. Small personal viewers typically rely on red, green, and

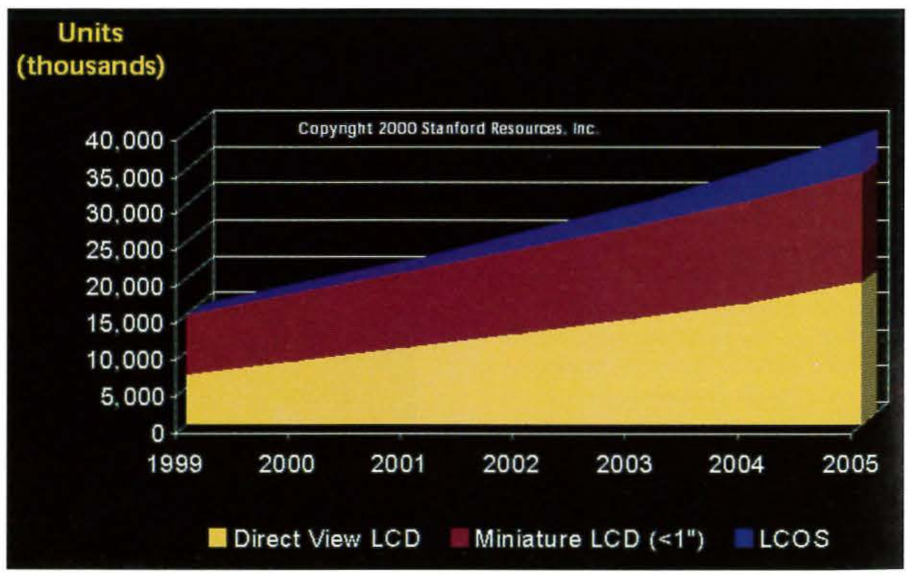


Fig. 5: LCoS microdisplays, miniature LCDs, and direct-view LCDs are all forecasted to experience growth in camcorder and digital-camera viewfinders.

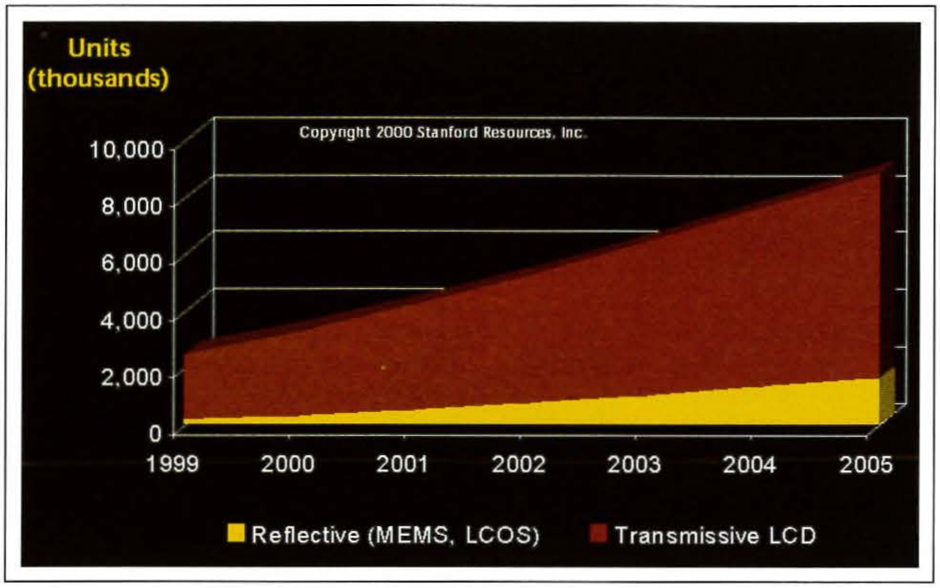


Fig. 6: *The use of microdisplays in projection-display engines, including projection TVs, are expected to grow substantially, but transmissive LCDs will dominate the segment.*

blue light-emitting diodes (LEDs) to illuminate sequential frames.

Numerous companies are pursuing LCoS devices (Fig. 4). The first devices reached the market in the form of displays made by IBM and JVC; Pioneer demonstrated an LCoS projector, but did not bring it to market.

Transmissive microdisplays. Transmissive microdisplays all use LC technology. Due to the high performance requirements – number of pixels, number of colors, and video speed – all such devices are active-matrix designs that use TFTs to control individual pixels. TFTs for transmissive microdisplays are made either from polycrystalline silicon (poly-Si) or from single-crystal silicon transferred to glass.

Poly-Si TFT-LCDs are typically fabricated on quartz-glass substrates in a process similar to large-area amorphous-silicon (a-Si) TFT-LCDs. The main difference is the addition of a high-temperature annealing process to recrystallize the deposited silicon. The higher electron mobility and smaller device sizes of poly-Si TFTs make it possible to create higher pixel densities than with a-Si TFTs.

Most poly-Si TFT-LCDs produced to date have been larger than 1 in. on the diagonal. As a result of refinements for use in projection systems and viewfinders to increase the effective aperture ratio, 0.7-in. poly-Si TFT-LCD devices and microlens arrays have been recently introduced. Seiko-Epson and Sony are the leading producers of poly-Si TFT-LCDs.

Kopin Corp. has developed a process for constructing miniature AMLCDs by fabricating TFT arrays on silicon wafers and then removing the array and attaching it to a glass substrate. Low-resolution low-cost versions of these devices are in production for applications such as digital-camera viewfinders.

Emissive microdisplays. In principle, the simplest type of microdisplay is a light-emitting device because it eliminates the need for an external light source. Most of the known emissive FPD technologies have been implemented as microdisplays, although none are in production. (But millions of miniature CRTs are used in camcorder viewfinders.) The low luminance levels of emissive microdisplays have limited their application to personal viewers.

Electroluminescent (EL) displays convert electrical energy directly into light. Thin-film techniques are used to deposit the stacked layers of metal electrodes, insulator, and phosphor material (typically, doped zinc sulfide). Planar Systems produces active-matrix EL microdisplays on a 0.7-in.-diagonal substrate with 640×480 pixels and 1000-lpi resolution. Devices with 1280×1024 pixels at a resolution of 2000 lpi have been demonstrated. EL devices require high voltages (80 Vac) to operate, necessitating the use of silicon-on-insulator substrates that isolate the high-voltage signals from non-selected pixels and logic. LC shutters are required to achieve full color because of problems in creating blue-emitting phosphors.

Field-emission displays (FEDs) are vacuum devices that utilize arrays of electron emitters

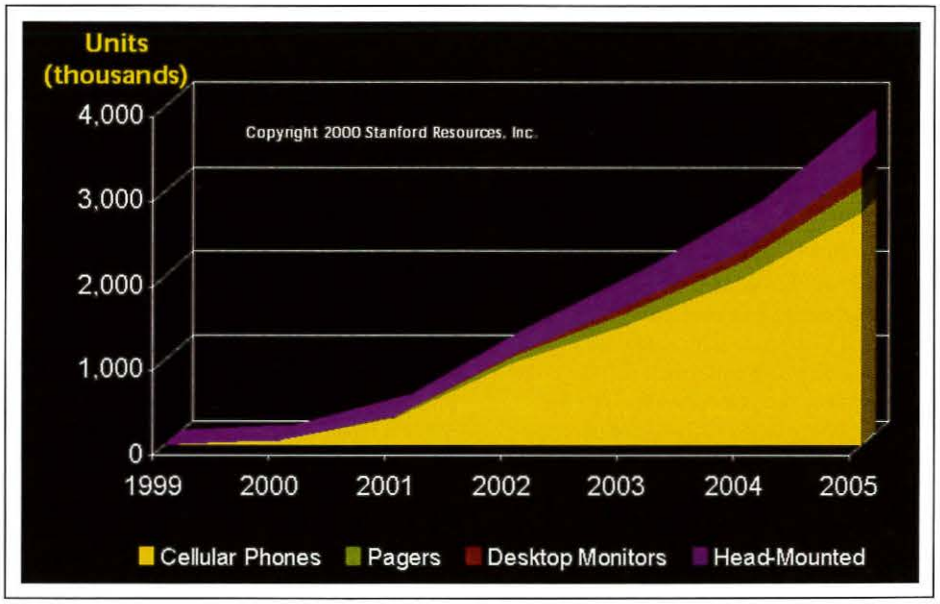
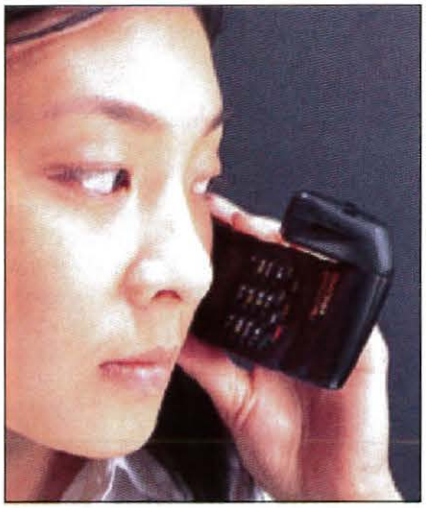


Fig. 7: *The largest new microdisplay applications are expected to be cellular phones and head-mounted displays.*



Kopin Corp.

***Fig. 8:** This prototype from Kopin demonstrates how a microdisplay could be used in a cellular telephone. The application requires optics that offer good eye relief and a large exit pupil.*

(cathodes) to produce electrons, which are then accelerated toward a phosphor-coated faceplate to produce color images. Micron Display Technology – now part of PixTech – has developed monochrome FED microdisplays for military applications; these devices are 0.6 in. on the diagonal, with 545 × 222 pixels.

Typical vacuum fluorescent displays (VFDs) use a flat vacuum-tight glass package. They rely on the emission of light by phosphors exposed to electrons emitted from a series of filaments. Display Research Laboratories is developing VFD microdisplays in which micrograined phosphors are deposited on silicon substrates. A 0.4-in.-diagonal device with 172 × 108 pixels using an analog interface has been demonstrated.

Light-emitting diodes (LEDs) are typically fabricated as discrete semiconductor devices made of gallium arsenide material; the combination of holes and electrons across a p-n junction results in the emission of photons. Displays that scan red, green, and blue LEDs across the eye to form an image directly on the retina are under development. Similar devices using semiconductor lasers are also under development. Microvision has developed sample systems using LEDs, and is working on merging LED sources with a MEMS scanning element.

Organic light-emitting diodes (OLEDs) are LEDs fabricated with organic materials in a film-manufacturing process. eMagin (formerly FED Corp.) is developing OLED microdisplays on silicon substrates, using technology licensed from Kodak. Kodak has also initiated a joint development project with Sanyo to develop active-matrix OLEDs using poly-Si TFTs. This combination might be used to fabricate microdisplays.

Microdisplay Applications

As previously mentioned, microdisplays seem best suited for two types of system configurations: projectors and personal viewers. Emissive microdisplays are only appropriate for personal viewers, while the other technologies can be adapted for both applications. Within each segment, it is important to distinguish between existing markets and new markets.

In existing markets, the applications are mature, but they are often served by alternative display technologies. The largest existing markets for microdisplays are camcorder viewfinders, in which the market is currently divided between direct-view LCDs and microdisplays (Fig. 5), and projection displays, in which microdisplays are just beginning to have an impact (Fig. 6).

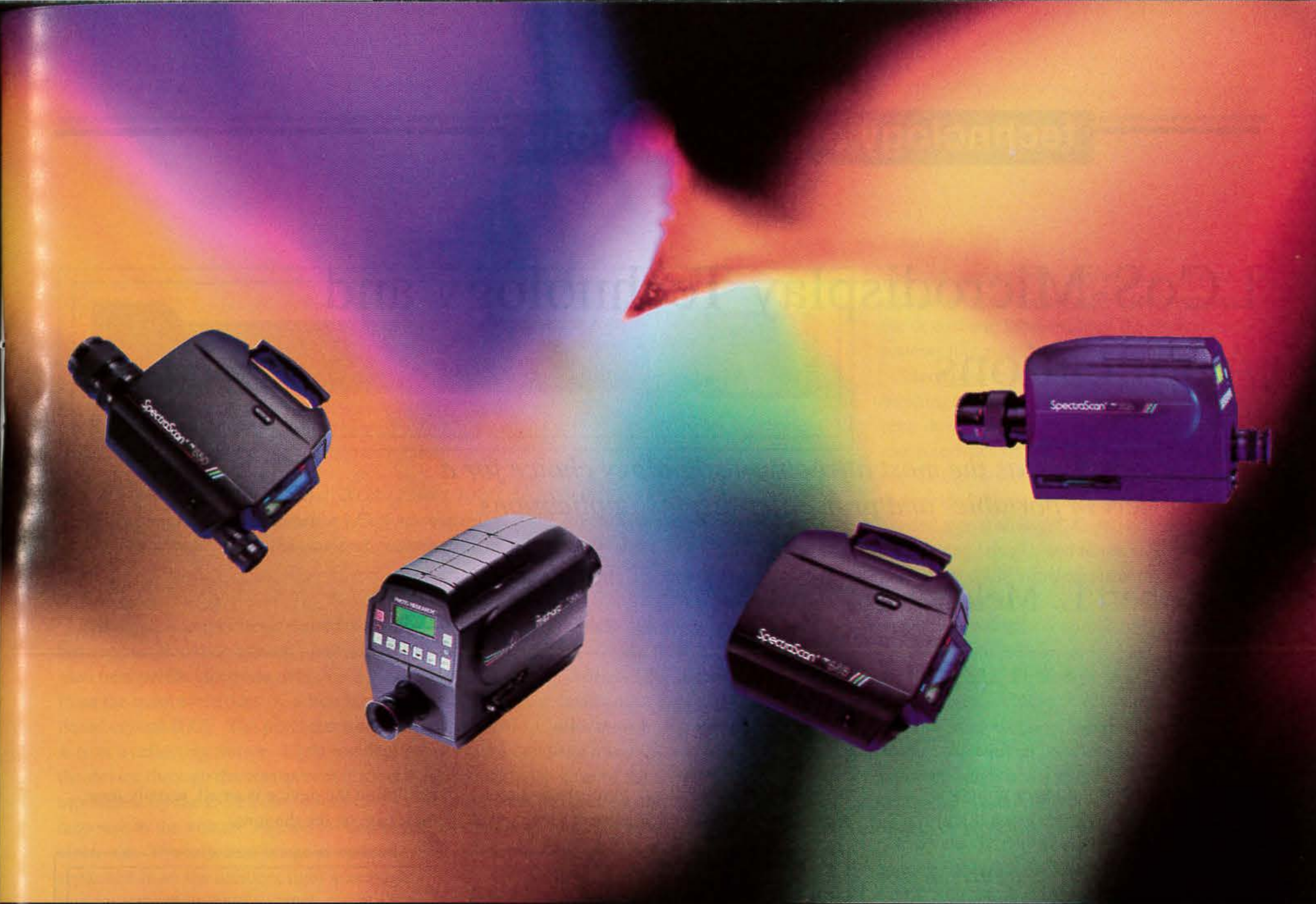
The applications in new markets are uncertain, but because they will be made feasible by microdisplays, these devices will face little competition from other display technologies. Potential new markets for microdisplays include cellular phones, pagers, desktop monitors, and headsets (Fig. 7). Cellular phones enabled by the wireless application protocol (WAP) standard make mobile Web surfing possible with reduced information content. Microdisplays offer the possibility of viewing the full content – at SVGA or better – of Web pages on cellular phones or mobile Internet appliances (Fig. 8).

Is the Future Small?

Microdisplays represent a new phase of display technology, raising the possibility of significant changes to the current industry structure and existing product applications as well as the creation of new display-based products. The devices demonstrated to date have compelling technological and potential economic benefits. The high level of interest among established firms and start-up efforts suggest that the necessary critical mass exists to create a new class of products. In addition, the possibility of leveraging existing semiconductor foundries adds to the momentum of the development effort by making start-ups faster and more affordable.

The implications for display markets fall into two broad categories. For established applications, mainly projection, microdisplays will have the opportunity to sell to large and growing markets. However, they will face competition from entrenched technologies that, in some cases, provide price/performance ratios that will be difficult to surpass. In new applications, primarily personal viewers, microdisplays have the distinct advantage of being the technology that enables the products, so they face little competition from other technologies. In these markets, the biggest hurdle is market acceptance. Finally, these new markets require the development of associated infrastructure, such as increased wireless bandwidth for mobile communications and the creation of content and delivery systems for high-definition-television programming.

While many questions remain about the ultimate role of microdisplay technologies in high-density displays, the future of displays may be small. ■



LCoS-Microdisplay Technology and Applications

LCoS is emerging as the most attractive technology choice for a wide variety of portable- and projection-display applications.

by Robert L. Melcher

SINCE the first reports of prototype projection-display systems using liquid-crystal–on–silicon (LCoS) microdisplay technology,[1–3] the promise of high performance at low cost has led to numerous development programs targeting a broad range of display applications. Developers have made significant progress in LCoS-device design, performance, and fabrication. LCoS devices with resolutions ranging from QVGA (320 × 240) to 2048 × 2048 have been successfully fabricated and used in products or prototype systems.

Parallel improvements have been made in the performance and cost of the optical components required to build a projection product, including lamps and illumination systems, prisms and coatings, screens, and projection lenses. These combined developments are poised to make a major impact on the four key applications areas for microdisplays.

We will review the technology elements that comprise a successful LCoS display, and look at their applications to display systems.

Technology

LCoS microdisplays are extremely small active-matrix liquid-crystal-display (AMLCD) devices that operate in a reflective mode. The active matrix is fabricated on a silicon chip using CMOS technology. Pixel sizes range from about 7 to 20 μm, so even for megapixel resolution the device is small, usually less than 1 in. on the diagonal.

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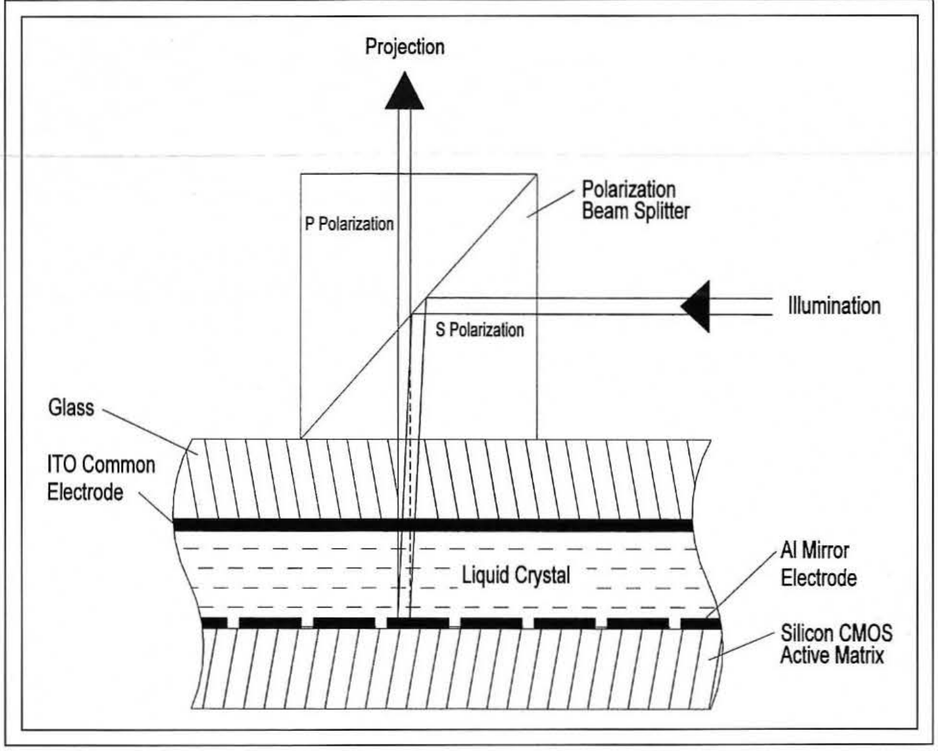

Fig. 1: This cross-sectional drawing of an LCoS device shows the optical layout. The silicon backplane consists of a standard CMOS process followed by a few processing steps unique to the microdisplay. The voltage applied by the active matrix across the individual mirror electrode and the common ITO electrode modifies the polarization of the incident S-polarized light. The part of the reflected light which has been electro-optically converted to P-polarization passes through the PBS and is projected onto the screen of a projector or onto a retina.

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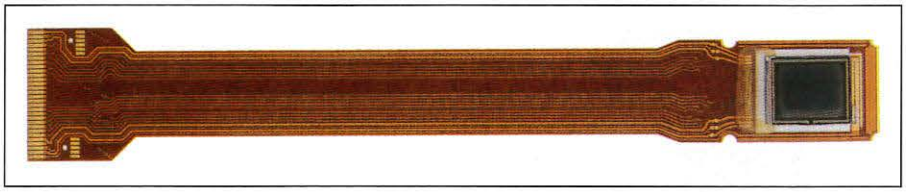

Three-Five Systems, Inc.

Fig. 2: *This Three-Five Systems SXGA (1280 x 1024) device with 12-μm pixels and a 0.78-in. array diagonal is a representative LCoS microdisplay. Data and timing signals are provided via the flex connection to the row-and-column drivers, which are integrated on the silicon backplane.*

The active-matrix circuit provides a voltage between an electrode at each pixel and a common transparent electrode, which is separated from the pixel electrodes by a thin layer of liquid crystal (LC). The pixel electrode also acts as a reflecting mirror. Light incident on the device through the transparent electrode is modulated by the LC electro-optics in response to the voltage applied to each pixel electrode. The reflected image is optically separated from the incident light and magnified for projection onto a screen or onto the viewer's retina (Fig. 1).

The silicon active-matrix backplane of the device permits great flexibility in circuit design. The pixel size is generally not limited by the ability of the silicon technology to fabricate small devices. Rather, it is the optical system's ability to efficiently illuminate the array that puts a lower limit on the pixel size. Designers have successfully applied active-matrix arrays based on analog DRAM pixel circuits and digital SRAM circuits to LCoS microdisplays. They can readily integrate row-and-column drivers by using the basic CMOS capability of the silicon backplane; integrating additional function is an available design choice.

The choice of LC electro-optical mode and material for a reflective LCoS microdisplay is governed by the voltage available from the active matrix, achievable contrast and throughput, chromaticity, switching speed, alignment techniques, reliability, and availability. Normally black and normally white LC modes have been developed. LC modes include twisted-nematic modes with a wide variety of twist angles and polarization directions, polymer-dispersed scattering modes, fast binary ferroelectric modes, and vertically aligned nematic modes.

Even though the LC cell gap is typically somewhat smaller than that of transmissive displays, the pixel size in reflective microdisplays is much smaller than that of direct-view displays. Consequently, if conventional row or column inversion is applied, three-dimensional LC effects such as reverse-tilt disclinations can have a significant impact on image quality because of the fringing electric fields between pixels. To mitigate this, full frame inversion at frequencies of 85 Hz or more has become standard.

The packaging of an LCoS imager must provide electrical interconnects, thermal management, and appropriate light shielding (Fig. 2). The mechanical construction must be sufficiently robust to maintain the relative alignment between the three imagers at a subpixel level. However, it must not exert undue stress that would disturb the optical performance of the device.

To be useful, a microdisplay requires a sophisticated optical system. A number of different optical architectures have been developed for LCoS projection-display applications. Most of these utilize an arc lamp as a source. The optical system must collect the light from the lamp, polarize it, separate it into the three primary colors, direct the color components to the microdisplay(s), combine the reflected image(s), and project them to the front- or rear-projection screen.

In addition to lenses, the optical architectures make use of components such as polarization-conversion devices, retardation plates, mirrors and prisms for dichroic color separation and recombination, and polarizing beam splitters. Because of the high-intensity light incident on the microdisplay and other optical elements in the system, designers must carefully choose materials that do not degrade under intense illumination.

Until recently, the design and fabrication of the optical components were considered to be cost and performance barriers to the use of reflective LCoS technology. But progress in the design and fabrication of the optical components has greatly reduced these barriers.

Electronic subsystems, which provide meaningful image data to the display, have been developed to accommodate the unique characteristics of microdisplays. Complex ASIC chips are often used to format the data, to provide gamma correction, to provide needed signal strength, to provide the necessary timing signals, and to provide calibration and temperature compensation for the microdisplay.

Color-sequential or scrolling-color displays require additional electronic functions to operate effectively. Similarly, special electronics are needed to achieve field-sequential gray scale in microdisplays based on binary LC modes. As with all fixed-matrix displays, computational algorithms are needed to perform scaling between different pixel formats. These tend to be proprietary to the system provider.

Manufacturing

LCoS technology promises to provide high-performance high-information-content microdisplays at significantly lower cost than competing technologies. Silicon backplane wafers with the required planarization, light-blocking, and mirror layers are generally fabricated in a CMOS foundry and supplied to the microdisplay manufacturer as starting raw material.

Experience has shown that dicing the wafer into imager chips and going through the LC-cell process on an individual-imager basis is not as controllable or as cost-effective as a wafer-level cell process followed by singularization into individual imagers. An added benefit to wafer-level cell processing is the similarity of the process to more conventional LC-cell processing. With reasonable yield from the LC cell and packaging steps, the cost of the silicon wafer is the major component of an LCoS microdisplay's overall cost. Therefore, going to smaller pixel sizes and smaller LCoS microdisplay devices delivers a cost advantage.

Applications

Major market areas addressed by microdisplays include multimedia front projectors (fixed and portable), rear-projection computer monitors, rear-projection television, and near-to-the-eye (NTE) displays. Although LCoS

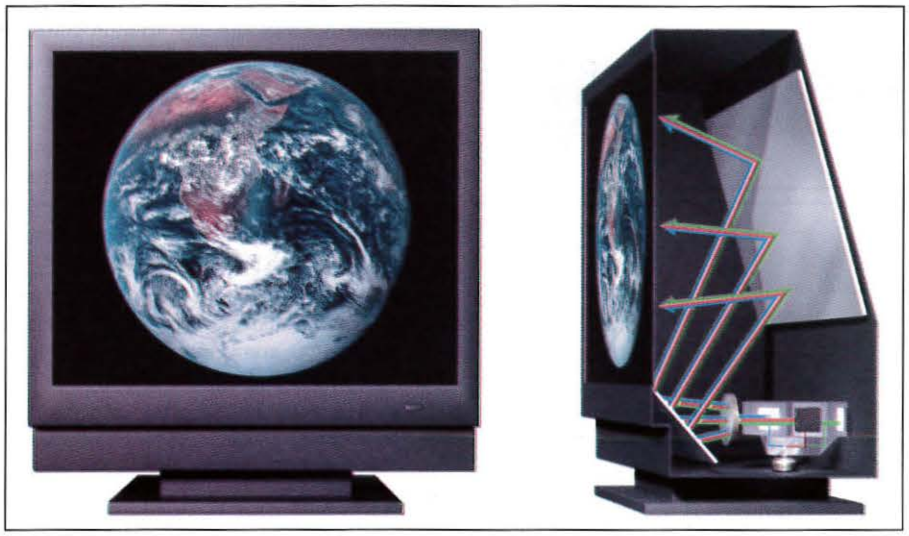

Fig. 3: A doubly folded optical path allows a rear-projection monitor or television to be made with a depth of about two-thirds the height of the image. A 58-in.-diagonal 16:9 screen can be built into a product that is about 20 in. deep.

competitors such as digital micromirror devices (DMDs) and transmissive polysilicon light valves address some of these markets, only LCoS is well suited to all of them.

The front-projection market is the best understood at this time. Although this market is growing rapidly and is currently dominated by polysilicon and DMD imagers, several high-end products based on LCoS have been introduced. Many of the performance targets – such as brightness and contrast – have been reached by each of these technologies. Attention is now being directed more toward physical size and weight, additional functions, user-friendliness, and, above all, price.

Price reductions at constant or improved performance have driven the expansion of the projector market. Up to now, LCoS microdisplays have played only a small role in driving this expansion. This situation appears to be on the verge of rapid change because of the advances being made in reducing the cost of LCoS imagers to levels well below competing polysilicon and DMD devices.

A particularly attractive feature of LCoS is its ability to provide a "family" of devices, each with the same active area but with different resolutions. In this way, a series of projector products can be designed to use the same optical system but provide images with different information content adapted to different markets.

Rear-projection computer monitors have been a favorite target for microdisplay technology because of LCoS's ability to provide high information content in a small (low-cost) device and, through projection, to provide a large-screen display with a relatively small footprint. But the excellent performance and low cost of the ubiquitous cathode-ray-tube (CRT) monitor have prevented successful market introductions. Most LCoS performance factors – including contrast, resolution, and optical efficiency – are now competitive with CRTs, but, at the moment, complete elimination of screen speckle can only be accomplished with some degradation of the image resolution. New screen technology is being developed to overcome this limitation.

The competition from CRTs and thin-film-transistor liquid-crystal-display (TFT-LCD) flat monitors will probably limit projection monitors to the large-screen high-performance segment of the market. CRTs with screens greater than about 24 in. become too large, heavy, and power hungry for the typical office environment. A wide-screen format, such as 16:9, with a display diagonal of about 28–32 in. is an attractive design point for a rear-projection monitor. A pixel format of 2560 × 1440 is needed for a 100-dpi image on a 29.4-in. screen with a 16:9 aspect ratio. This corresponds to four times the information content contained in a 720p high-definition-television (HDTV) image. The LCoS microdisplay is the most likely technology for such a monitor.

Television is a major market that is beginning to be addressed by LCoS microdisplays. HDTV and the convergence of digital TV with data displays will accelerate the introduction and acceptance of LCoS systems. HDTV refers to the digital formats 720p and 1080i – abbreviations for the pixel formats of 1280 × 720 with progressive scan and 1920 × 1080 with interlaced scan. Initially, almost all matrix-display technologies – such as LCoS, plasma, DMD, and TFT-LCD – are expected to make use of the 720p format, with digital conversion of 1080i or other formats to 720p. If market demand develops, LCoS will be capable of providing the 1080i format with line-doubling to effectively display 1080p.

The viewing distance for television in the average North American home is about 3 m. Combined with the average person's visual acuity limit of about 0.3 mrad, this implies that the smallest observable pixel on the screen is about 1 mm. This corresponds to a screen size of about 58 in. on the diagonal for the 720p format. The corresponding diagonal for a 1080i or 1080p HDTV is 1.5× larger, or 87 in. Although some investigators have said that a full evaluation of what HDTV viewers can actually see requires consideration of MTF as well as visual acuity [see, for example, R. L. Donofrio, *Information Display* **15**, 22 (June 1999)], it is clear that the greatest benefits of HDTV will be seen in the larger screen sizes. Only projection systems can provide these large screens economically.

The advantages of LCoS-microdisplay projection over the current technology, CRT projection, include a large increase in luminous output (and, consequently, better visibility in ambient light and a better viewing angle), much better definition of text for data applications, a smaller footprint achieved through folded optics (Fig. 3), lighter weight, and lower power. Color saturation, gray scale, and contrast are close to parity with projection-CRT technology.

Costs are expected to be competitive by the end of 2000, when microdisplay HDTVs enter the market. Because the cost of the microdisplay HDTV is not very sensitive to the pixel format, the 1080i format (with smaller pixels) will not be dramatically more expensive than the 720p format. However, that trend is also true for the lower-information-content standard-definition-TV formats such as 480p (704 × 480, rectangular pixel format), for which CRTs have a lower-cost structure. Consequently, microdisplays are initially expected to compete with direct-view and projection-CRT TVs most strongly in the large-screen high-definition segment, as well as in the data-convergence segment of the TV market.

Not Just Projectors

NTE applications of LCoS microdisplays include viewfinders for digital cameras and camcorders, head-mounted displays, and high-information-content displays for cellular phones and wireless Internet appliances. The required optical output is orders of magnitude lower than that of typical projector applications and can usually be generated by LED illumination sources. Only a single microdisplay is needed in NTE applications for either a monochrome or a field-sequential-color (FSC) display. The typical viewfinder today has the equivalent of QVGA (320 × 240) resolution. This requirement is readily satisfied by LCoS, and initial products are now being introduced. They tend to provide excellent images in a small package for a very cost-sensitive market.

Head-mounted displays (HMDs) for use in entertainment systems and wearable computers have generated significant interest but little commercial success so far. This may change as viewing comfort, size, weight, and cost improve. The rapid growth of the Internet and the wireless-telephone market, along with increases in available wireless bandwidth, are leading to a demand for fully mobile Internet appliances with the ability to display a full Web page without scrolling and without reformatting (see cover). The only technology available to do this at a resolution of SVGA (800 × 600) or higher is a microdisplay combined with the sophisticated optics needed to magnify the image with low distortion and provide a sufficiently large exit pupil to enable comfortable viewing. The wireless Internet appliance requires high resolution, low power, and small size. LCoS is the obvious technology for the application.

The Past Is Prologue

The commercial promise of the LCoS microdisplays has been largely unrealized until now, but it is about to become a mainstream display technology. LCoS will displace some current technologies in existing markets and will create new markets because of its unique characteristics. Indeed, developments occurring while this article was being written may well result in highly visible LCoS products within a few weeks of its publication.

Notes

[1]F. Sato, Y. Yagi, and H. Hanihara, "High Resolution and Bright LCD Projector with Reflective LCD Panels," *SID Intl. Symp. Digest Tech. Papers*, 997–1000 (1997).
[2]P. M. Alt, "Single-Crystal Silicon for High-Resolution Displays," *Conf. Record of the Intl. Display Research Conf.*, M19–M28 (1997).
[3]R. L. Melcher *et al.*, "Design and Fabrication of a Prototype Projection Data Monitor with High Information Content," *IBM J. R&D* **42**, No. 3/4, 321–338 (May/July 1998). ■

Manufacturing LCoS Microdisplays

Building a high-quality fab involves knowing the processes and carefully modifying selected semiconductor- and LCD-manufacturing equipment. But where does the fab go? Ohio?

by Michael Stefanov

MICRODISPLAYS might best be described as a "disruptive display technology." They have demonstrated images equivalent to the best laptops, monitors, and television receivers. They possess low-profile form factors, and light weight. They use much less power in personal-display applications. They cost much less than active-matrix liquid-crystal displays (AMLCDs), with prices that approach cathode-ray tubes (CRTs) of equivalent sizes.

Microdisplay markets encompass both the personal- and projection-display applications spaces (Fig. 1). The applications space for microdisplays can be broken down into headsets, embedded virtual displays, rear-projection systems, and front-projection systems. The total market revenue potential is estimated at greater than $500 million in 2000, growing to approximately $2.3 billion by 2004 (Fig. 2). Estimates of microdisplay pricing for near-term applications as a function of line definition are given in Fig. 3.

Market analysis predicts that front-projection and embedded virtual displays will dominate in the near term. Headsets using microdisplays have a small or as yet unpredictable potential. Rear-projection opportunities are the largest market in the long term.

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Market Diversity Drives Technology

The diversity of the liquid-crystal–on–silicon (LCoS) microdisplay market demands a flexibility in LCD assembly unrivaled by any other flat-panel-display (FPD) technology. Handling and cleanliness are in line with semiconductor processing, which is even more demanding than thin-film-transistor (TFT) assembly practices.

The silicon backplane is by far the most expensive component in LCoS displays, and efficient use of real estate demands ever-tighter mechanical tolerances on the physical package. Adapting equipment and processes to handle thousands of units per day of a highly sophisticated device through numerous process steps is a challenge unlike any other encountered in the FPD industry. Efficient automated testing at the cell and imager levels presents the greatest challenge in the near term as the industry moves to volume production.

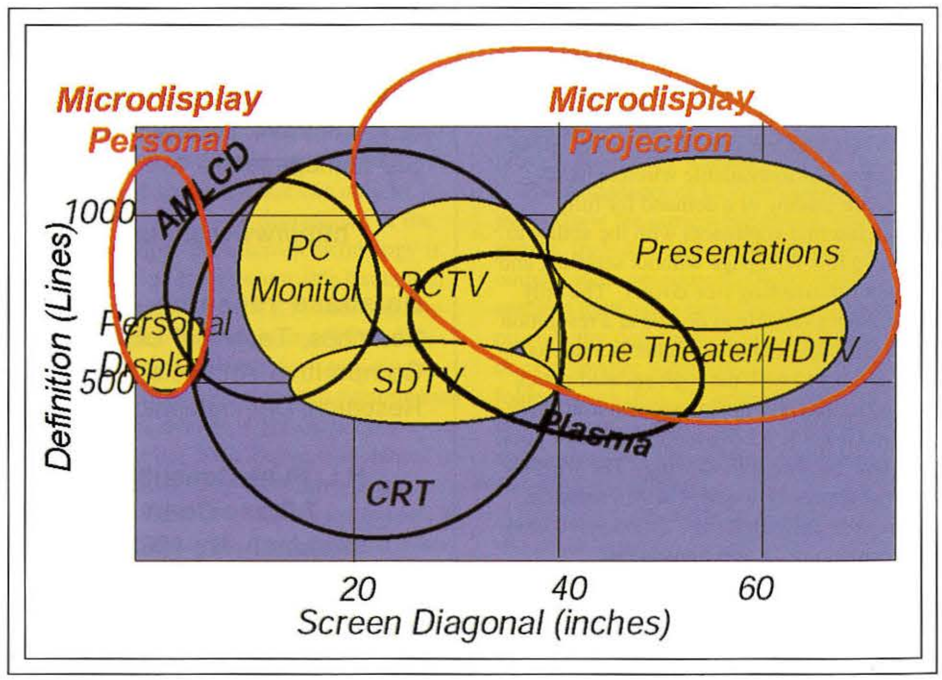

***Fig. 1:** Microdisplay markets encompass both personal and projection displays.*

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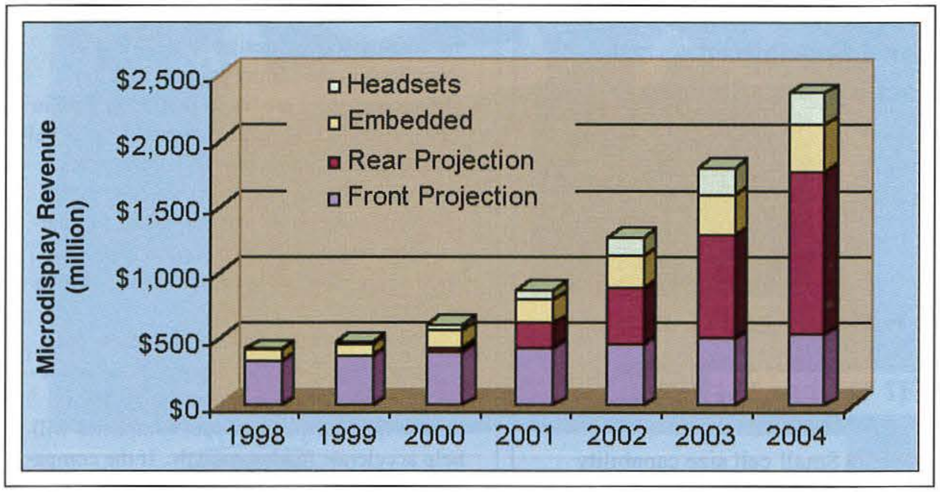

Fig. 2: The total market potential of all microdisplay applications is estimated at greater than $500 million in 2000, growing to approximately $2.3 billion by 2004.

LCoS displays used in high-magnification applications such as front projectors, monitors, and digital TVs have a very different set of performance criteria than virtual displays for near-eye applications. High-magnification applications place a premium on high contrast, high optical efficiency, and optical uniformity. These applications demand elevated operating temperatures and reliability under high optical flux, with drive voltages less than 5 Vrms.

Pixel dimensions determine the maximum LC-layer thickness and greatly impact the electro-optic mode and LC materials of choice. Eliminating spacers in the active area is always desirable if it doesn't compromise optical uniformity. When spacers are integrated into the display, cell gaps must be kept, typically, to less than 2 μm to keep associated artifacts invisible.

The decision to place spacers in the active area or not leads to two vastly different assembly processes. The glass counter-electrode needs to be of the highest optical quality and requires special coatings and handling. Lifetime issues associated with polyimide degradation under high-flux conditions, especially in the 400–420-nm range, have driven an intense industry-wide development effort among materials suppliers and device assemblers. Although sufficient lifetimes have been achieved, the materials are still not optimal, so work continues. Die mounting and electrical connections to the outside world – such as wirebonding or TAB – must be robust but cannot induce stress that might degrade cell uniformity.

Virtual displays must have response times capable of supporting field-sequential color (FSC). This dictates small cell gaps (1–2 μm) and the efficient use of drive voltage.

Market pressures to reduce cost are constant. The number of dice that can be processed per wafer leads to an ever-present demand on the LCD assembler to reduce the silicon area reserved for cell packaging. Imager packaging must be compact as well as robust and non-stressing. This has led to designs incorporating advanced materials, high-temperature FR4 (the composite used in printed-circuit boards), low-stress epoxies, and interconnect technologies such as ball grid arrays (BGAs) to reduce package volume.

Facility Issues

Over the past few years, wafer, or array-scale, assembly has emerged as a favored approach and is fast becoming the industry standard.

Efficient LCoS-microdisplay production requires the adaptation of semiconductor- and liquid-crystal-manufacturing tools in a dedicated facility. A philosophy of "custom-standard" should be applied when possible. This means that standard semiconductor- and LCD-manufacturing processes and equipment are to be customized for microdisplay manufacturing. This customization is most commonly directed at handling issues for the wafers or cells.

Standard TFT-LCD cleanroom requirements and practices for temperature, humidity, electrostatic-discharge (ESD) control, and services (electronics-grade deionized water, clean dry air (CDA), inert gases, *etc.*) are sufficient. Particle control over the substrates

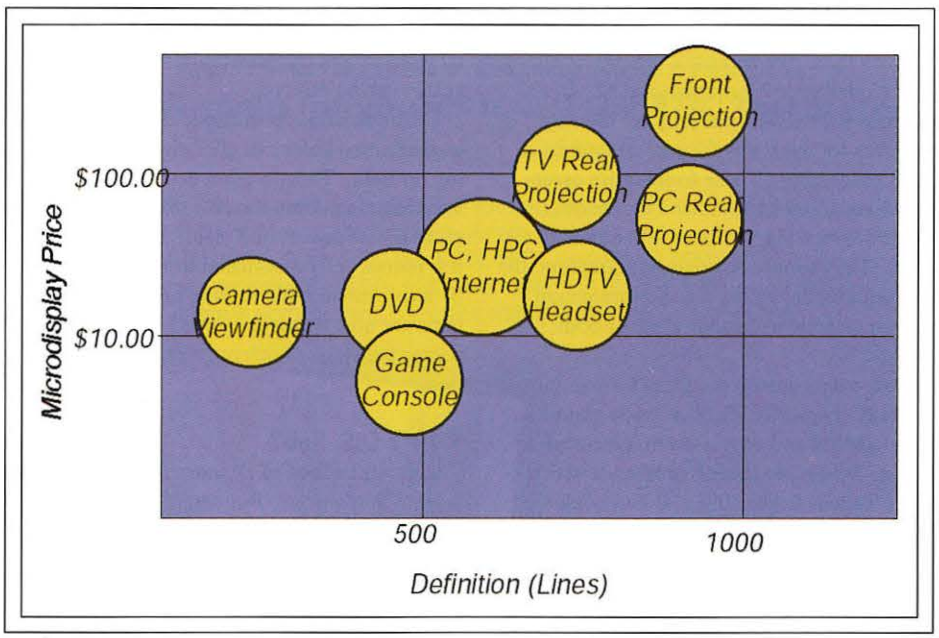

Fig. 3: Estimates of microdisplay pricing for near-term applications vary as a function of line definition.

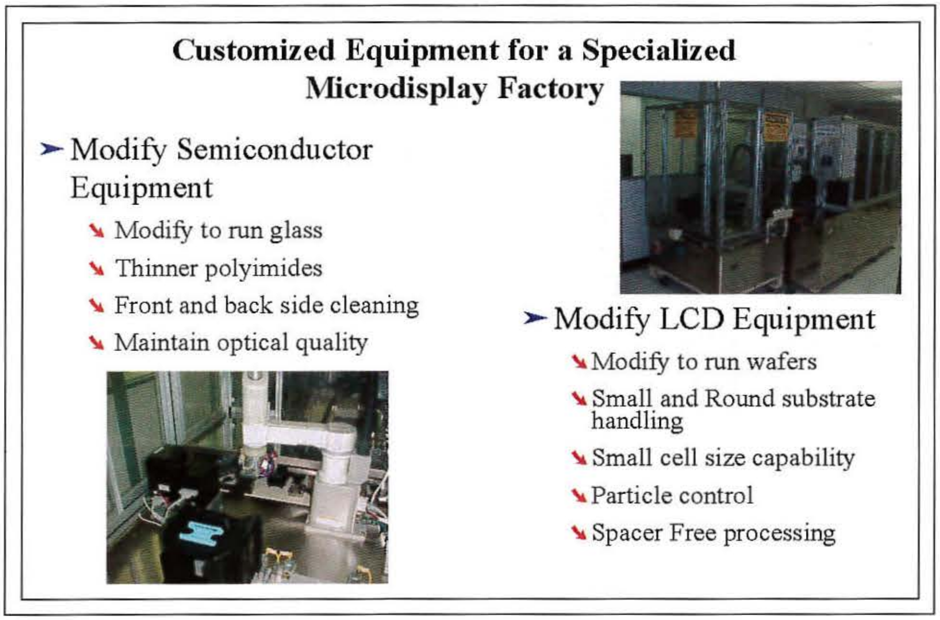

Fig. 4: *The modifications made to adapt LCD and semiconductor processing tools for LCoS manufacturing are usually in the areas of environmental control and – for the LCD equipment – automated materials handling.*

must be Class 1 or better for certain processes in which the substrate surfaces are open and exposed. This is best achieved through the careful specification and modification of equipment, installation of mini-environments, and the incorporation of cassette-to-cassette loading/unloading from standard mechanical interface (SMIF) pods.

Semiconductor Equipment and Materials International (SEMI) has long set industry standards for the wafer formats of interest in LCoS processing. These formats are essentially round, and have either a diameter of 150 mm with a single flat or 200 mm with a notch. They cannot be changed; therefore, the first requirement is that process equipment must be capable of handling one or both formats.

Next, a decision on the glass format must be made. Typically, display-grade glass is manufactured and processed in a rectangular format. While processing substrates with different formats is possible, it is cumbersome. If the glass can be processed through the line in the same form as the wafer, then LCD and semiconductor tools will require minimum modifications. These modifications are usually in the areas of environmental control and automated materials handling for the LCD equipment (Fig. 4).

Standard back-end packaging equipment, such as die bonders and aluminum wedge bonders, can be directly incorporated into the manufacturing process with very little modification. Cell- and package-cleaning procedures are similar to surface mount technology (SMT) processes. Standard LCD environmental test and qualification equipment and processes can be utilized.

Cosmetic and electro-optic tests can be implemented before or after electrical packaging, or both. This decision depends on many variables, including the cost of packaging materials and predicted yield. Regardless of test points, fully automated testing is going to be a requirement for volume production. Systems are now being developed, but all fall somewhat short of offering desired specifications.

Why a U.S. Fab?

The dominance of FPD manufacturing in Asia is beyond question. But determining where emerging products can be most efficiently developed depends on infrastructure, timing, and investment. Where is the technology being developed? At what stage of maturity is the technology?

The majority of microdisplay companies have their roots in semiconductor technology, not in FPDs. Many companies have followed the "fabless silicon design model" that is ubiquitous in the semiconductor industry. These companies are based predominantly in the U.S. or Europe, with the bulk of the development dollars going into U.S. companies. Many microdisplay products are now in the pre-production phase and are poised for market entry beginning in the second half of 2000, with plans for dramatic market growth in 2001.

A manufacturing partner who offers open communication, access, capacity, cost reduction, and shortened development cycles to fabless microdisplay-product companies will help accelerate market growth. If the companies exist on the same continent, there is a logical advantage. This is especially true if the manufacturing partner is not a product company and will never be a competitor.

Manufacturing Partners

Hana Microdisplay Technologies Inc. (HMTI) saw the need for a microdisplay-manufacturing service provider. HMTI's business philosophy is to be a contract-manufacturing partner to fabless microdisplay companies and a second source to companies with their own fabs. We are not a product company and will never compete with our product-producing customers.

HMTI is currently in the first phase of a 12-month capital expansion that will culminate in an assembly capacity of 1.5 million microdisplays per year. We intend to leverage the world-class microelectronics packaging and test expertise of the other members of the Hana Electronics Group as demand increases. HMTI's first microdisplay fab is in Twinsburg, Ohio, and we plan an expansion in Asia when demand dictates. The Asian facility will concentrate its efforts on manufacturing mature products and electronics packaging. The U.S. facility will concentrate on technology development and the manufacturing of new products and quick-turn prototyping. ■

Plastic LCDs to Roll?

Thinner, lighter, brighter, integrated displays can be produced by roll-to-roll processing, but some of the processes need more development.

by Joseph DelPico, Kuang-Chou Chang, and Gary D. Sharp

DESPITE great advances in technology, millions of people still get daily information from newspapers, which are produced inexpensively on printing presses that process giant rolls of paper. What if high-density full-color information displays could be produced on roll-to-roll equipment? And what if they could be thinner, lighter, and brighter than existing liquid-crystal-display (LCD) panels? This advance could pose a direct challenge to cathode-ray-tube (CRT) displays, which currently account for all but a few percent of the monitors and televisions produced worldwide.

The key problem with current direct-view LCDs is that they absorb too much of the transmitted light. Conventional designs use color-filter triads. Inherently, two-thirds of the available light is blocked by the color filters alone, even when the pixels are displaying white.

The solution maybe a new display technology that layers three controllable liquid-crystal (LC) cells with intermediate coated-polymer LC retarder stacks to provide full-color pixels. This results in a wide color gamut, a wider viewing angle, and more than six times the light transmission of current dual-scan supertwisted-nematic (DSTN) displays.

***Joseph DelPico** and **Kuang-Chou Chang** are with the Polaroid Corporation, 1265 Main St., Waltham, MA 02451; telephone 781/386-3406, fax 781/386-1340, e-mail: delpicj@polaroid.com. **Gary D. Sharp** is with ColorLink, Inc., Boulder, CO; telephone 303/545-5843, fax 303/545-5802, e-mail: sharp@colorlink.com.*

Stacked-Retarder Design

The new design uses stacked retardation films in front of and behind each LC panel to manipulate the state of polarization in a chromatically selective way. The design eliminates the need for intermediate analyzing polarizers; two external crossed polarizers are all it takes, which improves brightness and contrast ratio. The transmission of red, green, and blue light can be modulated individually (Fig. 1).

The retarder stacks determine the profiles of the red, green, and blue transmission spectra. ColorLink, Inc., has developed methods for designing the stacks for birefringent full-color displays. The input stack for each panel chromatically preconditions the polarization such that the panel modulates the polarization state of only one primary color. The exit stack is responsible for completing the polarization transformation, leaving the desired polarization component of the modulated primary color along the transmission axis of the output polarizer. Each filter stage is composed of two retardar stacks and an active birefringent LC panel that is invisible to the complementary subtractive primary.

For example, a layer might only affect the green component of a light source. The first retarder stack changes the polarization of just the green light, passing on the red and blue light unchanged. An LC layer also passes the red and blue, and either alters the green polarization or leaves it unchanged, depending on whether that cell is set to be ON or OFF. The second retarder stack then transmits the red

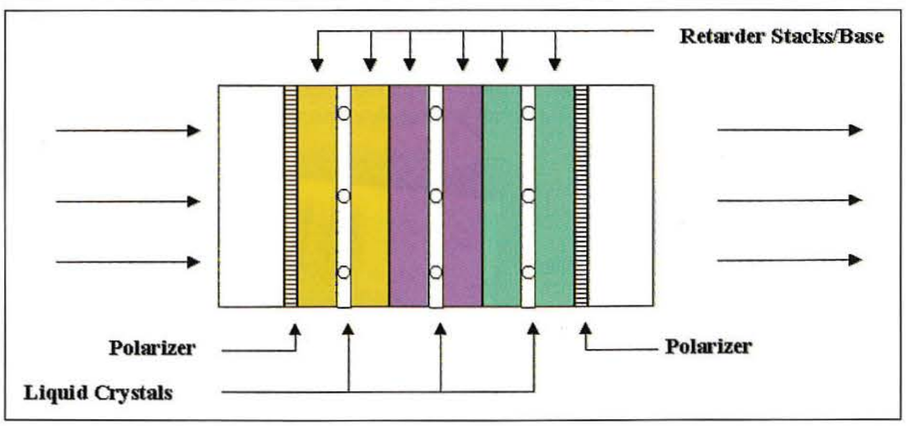

Fig. 1: Stacked retarders surround liquid-crystal layers to produce a full-color display with higher increased light transmission than that of traditional LCD designs.

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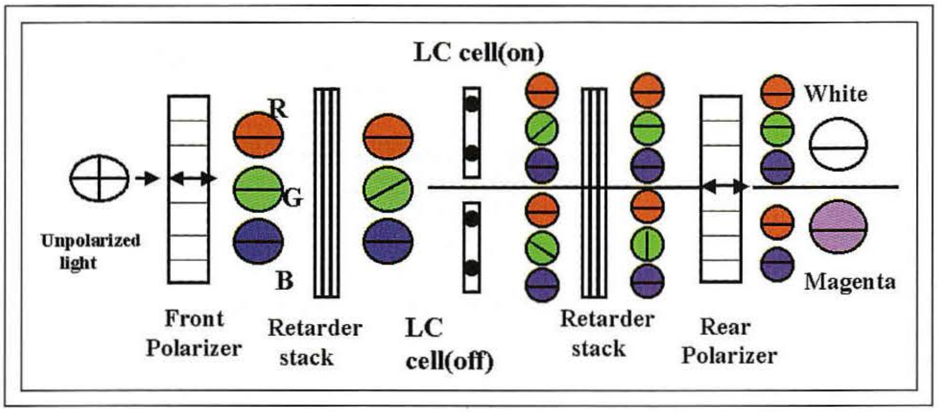

Fig. 2: Selective retarder stacks and liquid-crystal layers can be designed to transmit or block just green light resulting in a cell that appears as either white or magenta.

Table 1: Brightness of Complementary Color Test Cell

	Intensity (fL)	%T	Relative %T
Backlight	105.5	100	Transmission
DSTN display over backlight	6.48	6.1	1× (reference)
Birefringent cell over backlight	39.2	37.2	6.2×

and blue unchanged as before, and either blocks or transmits the green light, depending on the effect of the LC layer. The final result is that the cell will appear to be white if the LC layer is ON or magenta if the LC layer is OFF (Fig. 2). Similar stacks can produce yellow or cyan output. A full-color cell results when all three stacks are combined on top of each other forming a single pixel.

A single-pixel three-color test cell has been measured for comparison with a conventional DSTN display (Table 1). The DSTN panel transmitted only about 6% of the available light in its bright state, but the test cell transmitted approximately 37% – more than six times as much light. For a direct-view display, this design could rival CRT luminance while still reducing backlight luminance. For reflective panels without a backlight, the display should have acceptable brightness at much lower levels of ambient lighting.

Another benefit of this design is that the color gamut is increased significantly over that of a typical DSTN panel (Fig. 3). Tests on a magenta test cell also demonstrate that the absorption of green light can be controlled accurately by controlling the display voltage applied to the cell (Fig. 4). We have measured contrasts greater than 100:1 for a full-color display using this technology.

Parallax Reduction

The new design does require many more layers than a typical DSTN panel. If the technology were to be implemented with conventional components, the panel would be much thicker than normal. If glass LCD panels and conventional low-birefringence-polymer stressed-film retarders were used, the stacked display would have a total thickness of approximately 6 mm. When viewed off axis, the light path through the display would pass through points that were displaced by as much as four pixels from layer to layer (Fig. 5). The solution to the problem is to use much thinner materials for the display.

The first step is to use plastic in place of glass as the support film. By using 75-μm plastic support film, the individual LC panels may be as thin as approximately 155 μm. The other key step is the use of high-birefringence liquid-crystal-polymer (LCP) coated retarders instead of low-birefringence-polymer stressed retardation films. These LCP coatings are put directly on the plastic display's support films, with the thickness of each stack being approximately 15 μm. Thus, the thickness of the

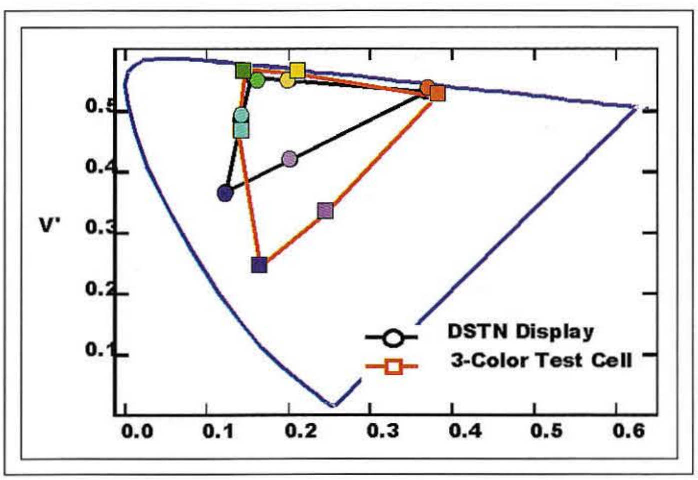

Fig. 3: The stacked-retarder design offers an increased color gamut compared with that of a traditional DSTN design.

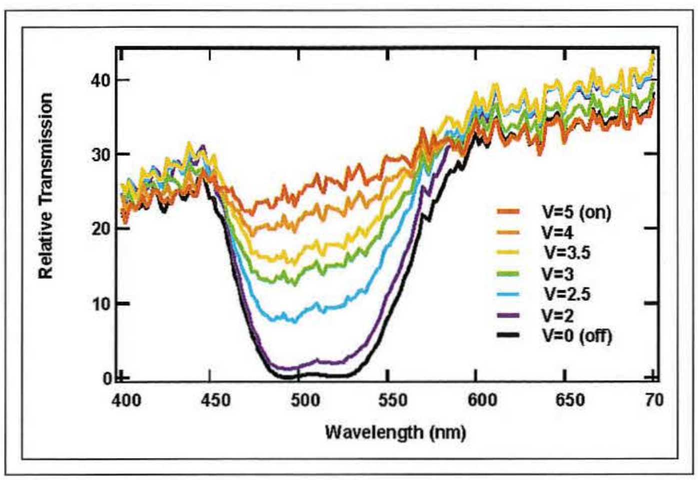

Fig. 4: The absorption of a given color of light can be controlled by varying the voltage applied to the cell.

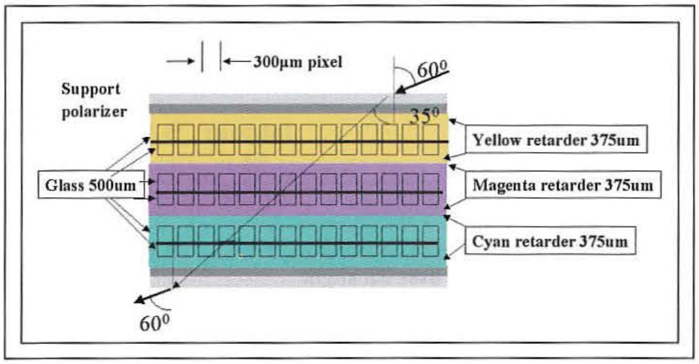

Fig. 5: Conventional materials are too thick for this stacked-retarder design; parallax problems greatly reduce resolution when viewed off-axis.

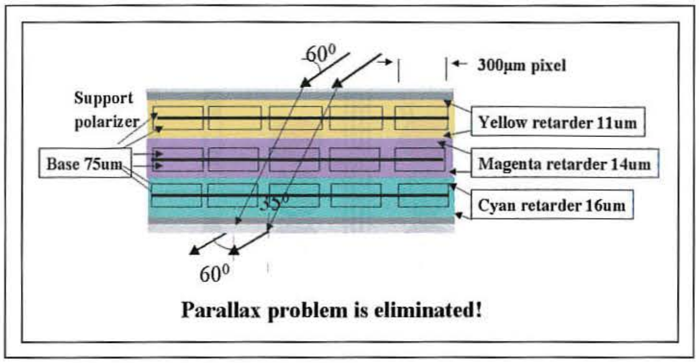

Fig. 6: A thinner panel design reduces the parallax problem.

entire display may be only one-tenth that of a design based on glass display support and a structure based on low-birefringence stressed retardation films. Even at large viewing angles, an optical-ray path through the entire panel will not span more than two adjacent 300-μm pixels (Fig. 6).

Moreover, since the pixels in question are each full-color elements – not separate adjacent color-triad segments – the effect of parallax is just a slight reduction in resolution rather than a large color shift due to adjacency crosstalk between subpixels of different colors.

ROLIC Research has shown that thin solid-state optical-retarder layers of this type can be produced from LCP films aligned by linearly photopolymerized (LPP) layers. Because of their strong optical anisotropy, the change in the refractive index (n) of LCP materials ranges from 0.07 to 0.3. A thickness of less than 2 μm may be necessary to achieve a half-wave optical LCP retarder film.

To manufacture the LPP/LCP retarders, the substrate must first be coated with photosensitive LPP material, and the LPP layer must then be photoaligned using linearly polarized UV light. A monomeric cross-linkable LC coating is then placed on top of the photo-aligned LPP layer and finally cross-linked with isotropic UV light. The required passive retarder-layer orientations are achieved by selecting the polarization direction of the UV light.

LPP/LCP retarder film can be applied to a plastic support substrate in a roll-to-roll process using standard film-coating techniques. Stacks of LPP/LCP retarders can be made by sequential coating and UV exposure in a single pass. Multilayered stacks of differently oriented retarders can feasibly be made at low cost.

In addition to optical LPP/LCP retarders with in-plane optical axes, a pre-tilt angle can be generated during the LPP exposure process to produce out-of-plane optical axes. The LC molecules of a subsequently coated LCP layer reproduce this tilt. The tilt angle can be adjusted in a wide range from 0 to 90°, depending on the LPP and LCP materials. By choosing the proper combinations of these oblique-optical-axis layers, the displays should have high luminance and chromatic stability over a wide viewing angle.

Roll-to-roll coating and assembly processes should result in low manufacturing costs, and they can be used to produce either transmissive or reflective flat-panel displays with wide color gamut and high optical efficiency (Figs. 7 and 8). In a market where it's difficult to be too thin or too bright, this new stacked-retarder design for LCDs may produce a new breed of lighter, brighter, and thinner displays that can be made with significantly more efficient production processes, resulting in lower costs. ■

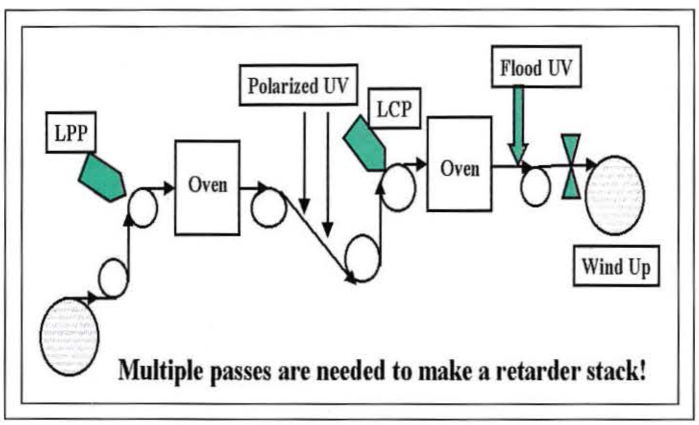

Fig. 7: Roll-to-roll production techniques can be used to create the retarder stacks.

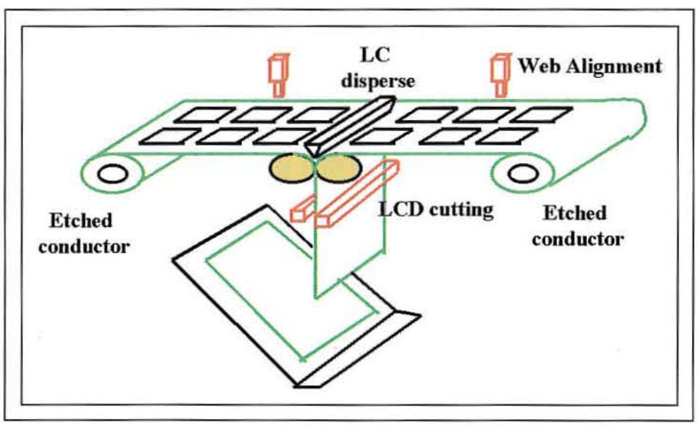

Fig. 8: Reflective or transmissive flat panels can be produced at low cost using roll-to-roll assembly processes.

conference preview

The First International Display Manufacturing Conference

IDMC, an international display-manufacturing conference and show held in Asia, with papers delivered in English, promises to be a uniquely valuable event.

by Jin Jang and Ken Werner

THE First International Display Manufacturing Conference will be held September 5–7, 2000 at the Sheraton Walker Hill Hotel and Conference Center in Seoul, Korea (Fig. 1). It will be an international gathering of scientists, engineers, display manufacturers, and users, where all aspects of display manufacturing will be presented, discussed, and evaluated. The event is being organized by the Korean Chapter of the Society for Information Display (SID), the Korean Display Society (KDS), the Korean Information Display Society (KIDS), the Korean Institute of Electrical Engineers, the Korea Research Foundation (KRF), the Korea Science and Engineering Foundation (KOSEF), and the Electronic Display Industrial Research Association of Korea (EDIRAK). EDIRAK and SEMI Korea will manage the associated exhibition, FPD Expo 2000.

As is true of all SID meetings, the official language of IDMC will be English, which will be the language for all presentations and the language in which the Conference Digest, both the printed and CD-ROM versions, will be published.

The meeting will present the latest information on the complete range of materials, components, manufacturing processes, and manufacturing equipment related to all of the major information-display technologies: liquid-crystal displays, plasma displays, organic light-emitting diode and electroluminescent displays, and field-emission displays and flat CRTs. The wide range of activities will include a keynote address by John Koo (President and Vice Chairman of LG Electronics), an opening address by Aris Silzars (the Presi-

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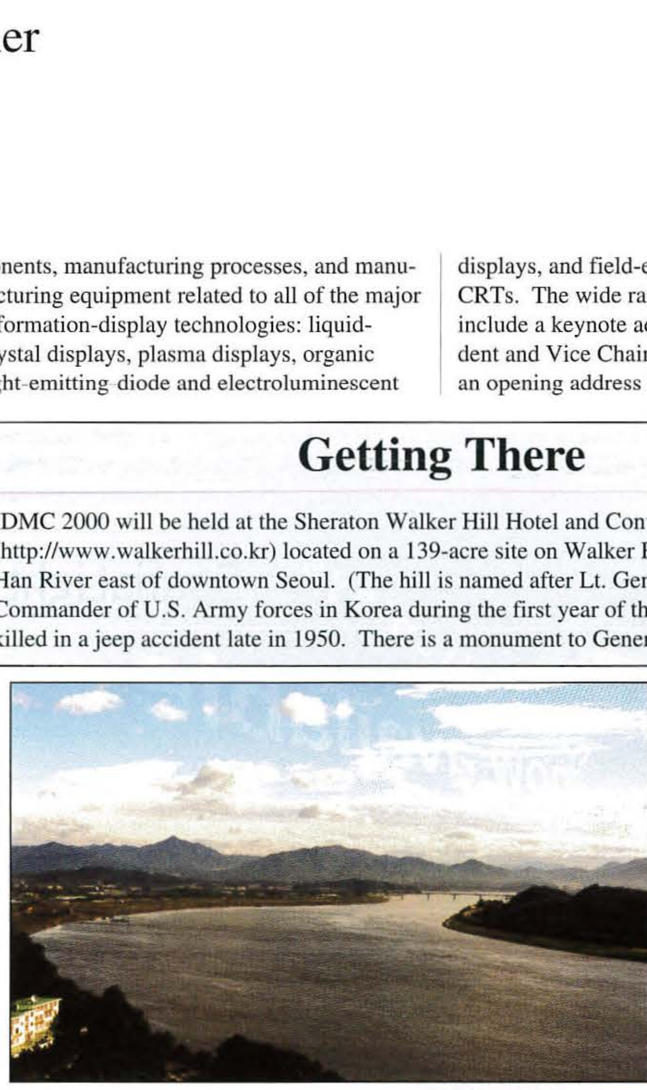
Getting There

IDMC 2000 will be held at the Sheraton Walker Hill Hotel and Convention Center (http://www.walkerhill.co.kr) located on a 139-acre site on Walker Hill, which overlooks the Han River east of downtown Seoul. (The hill is named after Lt. Gen. Walton H. Walker, Commander of U.S. Army forces in Korea during the first year of the Korean War, who was killed in a jeep accident late in 1950. There is a monument to General Walker on the hotel grounds.) The Han River flows along the base of the hill, providing an appealing view from many of the hotel's rooms.



Ken Werner

The Han River provides an impressive view from many of the rooms in the Sheraton Walker Hill Hotel.

Seoul is served by Kimpo International Airport. The KAL Limousine Bus (Line 4) leaves from Kimpo for the Sheraton Walker Hill every 15 or 20 minutes, starting at 6:10 a.m. and continuing until 10:00 p.m. The bus makes several stops along the way at various downtown locations. The fare is 4500 won. (On March 15th, the exchange rate was 1119 won to the U.S. dollar.)

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dent of SID), presentations of the latest developments in display manufacturing by key engineers and scientists who are making the advances at the world's display-manufacturing companies, in-depth reviews of important developments, and the FPD Expo 2000 exhibition of display components, materials, manufacturing equipment, test and measurement equipment, and display technology.

Keynote and Opening Addresses

John Koo's keynote address will discuss "Future Prospects of Flat Panel Displays in Korea." Koo is President and Vice Chairman of LG Electronics, one of the world's leading companies in the information-display business, including CRTs, LCDs, PDPs, OLEDs, and projections displays.

In his opening address, Aris Silzars will discuss "Display Manufacturing: The Next Ten Years." At the dawn of the computer age, existing display technologies – light bulbs, teletype machines, and then television-based monitors – provided more display capabilities than early computers could use.

Now, despite remarkable advances in display technology, the capabilities of both computer and entertainment systems are rapidly outstripping the capabilities of display devices. Affordable monitors are a very long way from being able to replace print – even the print produced by a $100 ink-jet printer – and large-screen entertainment displays are too expensive and not sufficiently bright.

Silzars will challenge his IDMC audience by asking, "What displays will you be manufacturing over the next ten years?" And He will emphasize a point he has made repeatedly in his regular *Information Display* column: "Real breakthroughs occur at the materials level." As those members of the display community who read the column know, Silzars' knowledge of the display industry is deep and his interests are broad. This can produce unexpected, enlightening, and often entertaining connections.

Technical Program

There will be approximately 100 technical papers, of which approximately 40 will be invited from the world's leading practitioners. The IDMC Technical Program Committee has consulted with a distinguished International Advisory Committee to extend these invitations to distinguished speakers working on issues of practical importance to the development of display manufacturing and technology.

Among these issues is the status and manufacturability of non-traditional emissive displays. The issue is addressed in several of the invited papers, including

- *Recent Progress in Organic Light-Emitting Devices* (J. Kido, Graduate School of Engineering, Yamagata University)
- *Electroluminescent Displays* (Hajime Inuzuka, Production Engineering R&D, DENSO Corp.)
- *Printed Field-Emission Structures* (Richard A. Tuck, PFE Ltd.)
- *Nanotube FEDs* (Jong Min Kim, Samsung Advanced Institute of Technology)
- *OLEDs* (Sungtae Kim, LG Corporate Institute of Technology)
- *Novel Pixel Structure for Organic Emissive Displays* (Yang Yang, UCLD)

With Toshiba's announcement that it had expanded the low-temperature-polysilicon (LTPS) facility in its Fukaya plant to obtain a production capacity of 150,000 10.4-in. LCDs per month (on an input basis), LTPS AMLCDs reached a new milestone. One of the keys to successful high-volume commercialization is a laser annealing process that is well characterized, consistent, and has high throughput. Among the invited papers that address these issues are

- *Effect of Laser Crystallization Conditions on Poly-Si TFTs* (Stan Brotherton, Philips Research)
- *Poly-Si TFT-LCD Manufacturing* (D. K. Kim, LG Philips LCD)
- *Current and Future Technology of Low-Temperature Poly-Si TFT-LCDs* (Y. Oana, Toshiba Corp.)
- *Optimization of LTPS TFTs and Manufacturing for a Large-Scale Display* (Kiyoshi Yoneda, Sanyo Electric Co.)

Designing, optimizing, and integrating LCDs – whether or not they use LTPS TFTs – for particular applications are critical activities that will grow sharply as new displays are incorporated into an ever-growing number of systems. The issues will be addressed in a number of papers. A few of them are

Welcome to Seoul

Korea has a rich culture and interesting history. Seoul has many museums and medieval palaces that are open to the public for very modest admission fees, which sometimes include a guided tour. The Korea House Theatre offers regular performances of traditional Korean music and dance in a building based on traditional Korean architecture. The Sheraton Walker Hill has one of the few privately owned museums in Seoul, with 450 works of mostly modern Western and Asian art. The museum is within the convention center. Admission is free.

This is the 50th anniversary of the Korean War, and many memorial events will be held across the country between June 24th and September 30th. Korean War veterans are particularly welcome.

Extensive tourist information is available from the Korea National Tourist Organization (http://www.knto.or.kr/).

Ken Werner

A pavilion and pond in Piwon (Secret Garden), part of the extensive and beautiful grounds behind the 14th-century Ch'angdokkung (Changdok Palace) in Seoul.

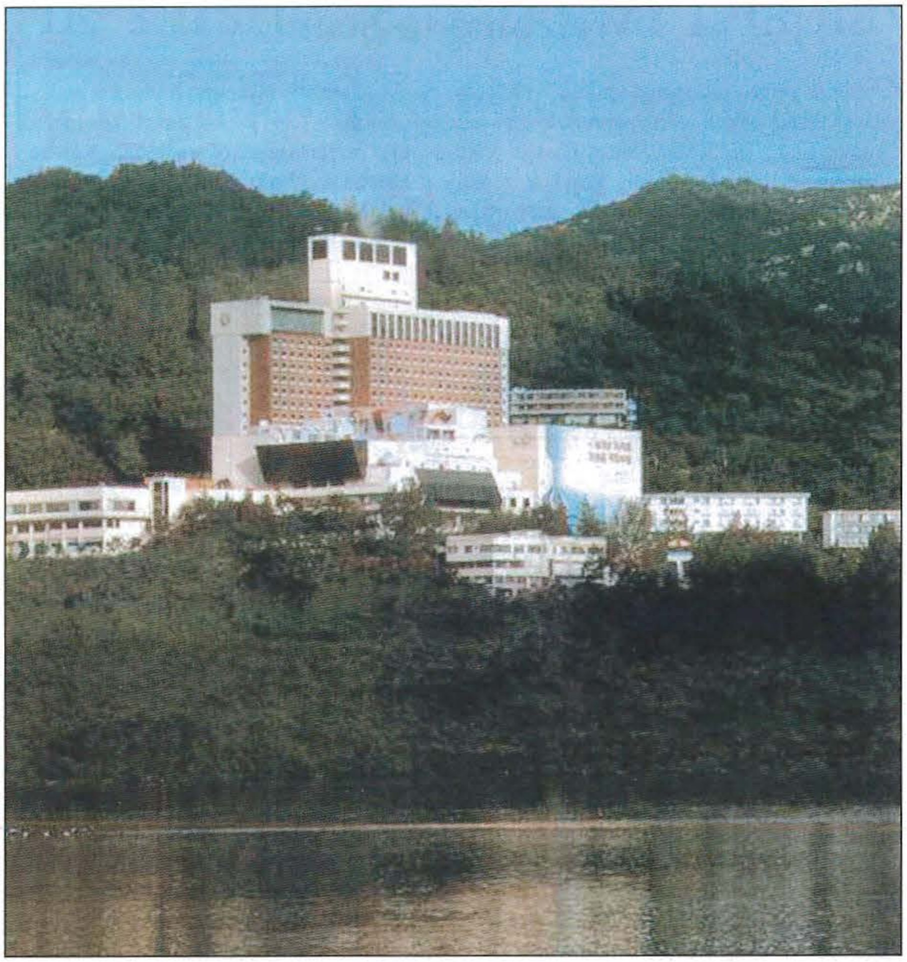

Fig. 1: *The Sheraton Walker Hill Hotel, sitting above the Han River, will host IDMC 2000. The convention center is connected to the hotel.*

- *Liquid-Crystalline Materials for Active-Matrix Display Uses: Electric Properties in Bulk and Performance in Cells* (Shohei Naemura, Merck Japan Ltd.)
- *TFT-LCDs for TV Application* (J. H. Souk, Samsung Electronics)
- *Requirements for Large-Sized High-Resolution TFT-LCDs* (Toshihiro Ueki, IBM Flat Panels)
- *A Novel Bright Reflective Color STN-LCD with the ISR (Inner Scattering Reflector) Structure* (Tetsu Ogawa, Matsushita Electric Industrial Co.)
- *High-Efficiency Backlighting Systems for Direct-View LCDs* (Zhengda Pang, Institute for Microstructural Sciences)
- *Manufacturing Issues in Wide-Viewing-Angle TFT-LCDs* (Seunghee Lee, Hyundai Electronics Ltd.)
- *Wide-View Film for TFT-LCDs* (Yoji Itoh)
- *PECVD Process for Next-Generation TFT-LCDs* (Masao Kakimoto)
- *Four-Photolithography-Process Amorphous-Silicon Thin-Film-Transistor Array* (Hong Chen, ERSO/ITRI)

Just as important as information about technologies is the information about costs and markets that help us decide which technologies to pursue. Among the invited papers that provide exactly that kind of guidance are

- *Flat-Panel-Display Manufacturing-Cost Comparisons* (Joseph A. Castellano, President and CEO, Stanford Resources, Inc.)
- *TFT-LCD Manufacturing Trends and Forecast* (Ross Young, President and CEO, DisplaySearch)

"This conference will surely be a unique and important forum for everyone working in or requiring technologies in the field of display manufacturing," said Prof. Sungkyoo Lim, IDMC Secretary General. "IDMC will be a big marketplace for the companies producing and manufacturing display materials, components, and equipment, as well as flat-panel displays for computer and TV applications. All companies producing display-related products are cordially invited to participate in this first International Display Manufacturing Conference."

An unusual feature of the conference will be a session for the presentation of new products. Any company wishing to introduce its quality products to the attendee will be welcome to make a 15-minute presentation.

Contact the Conference Coordinator at http://tftlcd.kyunghee.ac.kr/idmc for information and applications.

For additional information about the conference and registration, contact Prof. Sungkyoo Lim at limsk@ns.dankook.ac.kr. ■

Please send new product releases or news items to Information Display, c/o Palisades Institute for Research Services, Inc., 411 Lafayette Street, 2nd Floor, New York, NY 10003.

continued from page 4

I'm going to suggest an answer, but with the proviso that if you have a better one or a different one, you must let me know. Why? Because the answer has important implications for how we position SID and represent our display community to the rest of the high-technology world over the next decade.

My conclusion is that we are falling behind. Twenty years ago, displays, built on the solid foundation created by television and instrumentation applications, had more than adequate capability for the first rudimentary PCs and video games. For playing simple games like "pong," a monochrome CRT screen did not present a limitation. Today, the best CRTs and LCD panels are still a reasonable match for desktop computers and perhaps barely adequate for portable laptop computers, cellular phones, and first-generation PDAs. But what happens next? Although it is difficult to quantify all display parameters into a "goodness" factor, and I have no intention of trying to propose a parallel to Moore's law for displays, my best estimate is that display capability is doubling no faster than about every 10 years. If I am correct, then we have a serious rate-of-development mismatch that will soon require resolution.

Because of 40 years of television and instrumentation developments, displays were way ahead of what computers needed in the 1980s. Today, it seems to me that we are at no better than parity. And maybe not even that good. At our present rate of progress, in another 10 years we will have become the highly visible bottleneck of the Internet society.

Over the last two decades, investment money has flowed freely into microprocessors and memories, into software, and into Internet-commerce start-ups. With a few rare exceptions, we in the display community have had a more difficult time creating investor interest and then sustaining it until success could be demonstrated. Yet there is a need for sunlight-readable displays, large displays for desktops, low-cost and easy-to-see displays for portable Internet appliances, high-resolution displays in all sizes and all price ranges for the new digital-television applications, and flat panels of all kinds and sizes for low-cost multi-use home and commercial applications. Many of these new display applications are *not* simple product extensions of the traditional television displays or even of the newer desktop- or laptop-computer displays.

The good side of this is that there will be an increasing demand for these displays. The bad side is that when we become the limiting factor in the development of new products, there will be increasing frustration among the system and software designers that will manifest itself in increasing demands on the display community. In response, there are likely to be numerous attempts at quick fixes and perhaps even a few "leapfrog" approaches proposed. However, if the fundamental principles haven't been thoroughly understood and the basic materials are not fully developed, these attempts will fail.

The best that we can accomplish in bringing new display products to market in the next 10 years has to a large degree already been set by what we know today about the basic materials and processes for creating emissive, transmissive, or reflective displays. How well we meet the needs of our colleagues in the rest of the high-technology community over the next decade will now depend on how much enthusiasm we can generate in the investment community and within the larger corporations, while being realistic in telling the world what rate of progress can be expected.

The Society for Information Display will also have to be prepared to play a leading role as the growing need for better displays of all shapes, sizes, and functionality manifests itself. As the increasing popularity of display devices stimulates rapid change and increased competition, SID can and must respond to these needs as the premier organization that provides the international focal point for the exchange of technical information in all aspects of display technology. Of one thing we can be sure, in the next decade we will be living in interesting times.

To discuss this topic further, please contact me by e-mail at silzars@attglobal.net, by telephone at 425/557-8850, by fax at 425/557-8983, or by regular mail at 22513 S.E. 47th Place, Issaquah, WA 98029.

Aris Silzars is President of SID and lives on a hilltop in Issaquah, WA. ■

calendar

Microdisplay 2000. Sponsored by Displaytech, Inc., and the SID Southwest Chapter. Contact: United Engineering Foundation Conferences; 212/591-7836, fax -7441, e-mail: engfind@aol.com.
Aug. 7–9, 2000 Boulder, CO

The First International Display Manufacturing Conference (IDMC 2000) and Vendor Exhibition (FPD Expo 2000). Sponsored by the SID Korea Chapter and Korea Information Display Society. Contact: Prof. S. Lim, Secretary General; telephone +82-417-550-3542, fax -3592, e-mail: limsk@ns.dankook.ac.ker.
Sept. 5–7, 2000 Seoul, Korea

Twentieth International Display Research Conference (IDRC '00). Sponsored by SID. Contact: Ralph Nadell, Palisades Institute for Research Services, Inc., 212/460-8090 x203, fax -5460, e-mail: Rnadell@newyork.palisades.org.
Sept. 25–29, 2000 Palm Beach, FL

Seventh Annual Symposium on Vehicle Displays. Sponsored by the SID Detroit Chapter. Contact: V. Cannella; 248/540-7830.
Oct. 3, 2000 Dearborn, MI

The Sixth Asian Symposium on Information Display (ASID '00) and Information Display China 2000. Sponsored by the SID Asia Region, ITE, IEICE, and XJTU. Contact: Prof. C. Liu, Xi'an Jiaotong University; +86-29-2668657, fax -2668659, e-mail: chlliu@xjtu.edu.cn.
Oct. 18–20, 2000 Xi'an, Shaanxi, P.R. China

The Sixth International Conference on the Science and Technology of Display Phosphors. Sponsored by DARPA and SID. Contact: Mark Goldfarb, Palisades Institute for Research Services; 212/460-8090 x202, fax -5460, e-mail: mgoldfar@newyork.palisades.org.
Nov. 6–8, 2000 San Diego, CA

Eighth Color Imaging Conference: Color Science, Engineering Systems & Applications. Sponsored by IS&T and SID. Contact: Dee Dumont, SID HQ, 408/977-1013, fax -1531, e-mail: office@sid.org.
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Electronic Information Displays (EID 2000). Sponsored by SID. Contact: Trident Exhibitions, +44-(0)-1882-614671, fax -614818, e-mail: info@trident exhibitions.co.uk.
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The Seventh International Display Workshops (IOW '00). Sponsored by ITE and SID. Contact: IDW '00 Secretariat; +81-3-3423-4180, fax -4108.
Nov. 29–Dec. 1, 2000 Kobe, Japan ■

editorial

continued from page 2

Microdisplays remain an extremely attractive technology that will certainly explode this year – but slowly.

– KIW

We welcome your comments and suggestions. You can reach me by e-mail at kwerner@nutmegconsultants.com, by fax at 203/855-9769, or by phone at 203/853-7069. The contents of upcoming issues of *ID* are available on the *ID* page at the SID Web site (http://www.sid.org).

Please send new product releases or news items to Information Display, c/o Palisades Institute for Research Services, Inc., 411 Lafayette Street, 2nd Floor, New York, NY 10003.

SID 2001 honors and awards nominations

Once again, but the first time in the new millennium, as chairman of the SID Honors and Awards Committee, I am appealing for your active participation in the nomination of deserving individuals for the various SID honors and awards. These awards include the prestigious major professional prizes (the Karl Ferdinand Braun prize, the Johann Gutenberg prize, and the Jan Rajchman prize), the major society prize (the Lewis & Beatrice Winner award), the SID Fellow awards (five endorsements are needed), and the SID Special Recognition awards. The selection and nomination process is relatively simple, but requires that you and perhaps some of your colleagues devote some time to the preparation of the supporting material that the Honors and Awards Committee needs in order to evaluate each nomination for its merit.

Since 1997, nominations can be entered through the Internet simply by logging in at www.sid.org. At the SID Web site, in the SID Information Center box, click on ***Awards***. This action opens the Honors and Awards section of the SID site. Then click on the ***Nomination Form*** found on the middle of the page, *i.e.*, the display screen, to open the Nomination Form. The "How to Use This Form" box at the beginning of the Nomination Form very simply explains how you can use this electronic form to nominate someone for any of the prizes or awards. The SID Honors and Awards Committee encourages the use of this electronic version. Volunteer labor is used to process all the nominations. Electronic filing saves a lot of administrative work, and helps with reducing the workload on our volunteers. But we will still accept hardcopy nominations. The associated text box appearing in this column contains a complete description of each of the prizes and awards, along with a detailed description of the information that is asked for in support of each nomination. ***Please note the continuation of a new policy instituted last year. With each Fellow Award nomination, five written endorsements by five SID members will be required. These brief endorsements – a minimum of 2–3 sentences to a maximum of one-half page in length – must state why, in the opinion of the endorser, the nominee deserves to receive the Fellow Award. Identical endorsements by two or more endorsers will be automatically***

SID honors and awards nominations

Nominations are now being solicited from SID members for candidates who qualify for SID Honors and Awards.

- FELLOW. Conferred annually upon a SID member of outstanding qualifications and experience as a scientist or engineer in the field of information display, and who has made a widely recognized and significant contribution to the advancement of the display field.
- JAN RAJCHMAN PRIZE. Awarded for an outstanding *scientific* or *technical* achievement in, or contribution to, research on flat-panel displays.
- KARL FERDINAND BRAUN PRIZE. Awarded for an outstanding *technical* achievement in, or contribution to, display technology.
- JOHANN GUTENBERG PRIZE. Awarded for an outstanding *technical* achievement in, or contribution to, printer technology.
- LEWIS & BEATRICE WINNER AWARD. Awarded to a SID member for exceptional and sustained service to SID.
- SPECIAL RECOGNITION AWARDS. Granted to members of the technical, scientific, and business community (not necessarily SID members) for distinguished and valued contributions to the information-display field. These awards may be made for contributions in one or more of the following categories: (a) outstanding technical accomplishments; (b) outstanding contributions to the literature; (c) outstanding service to the Society; and (d) outstanding entrepreneurial accomplishments.

Nominations for SID Honors and Awards must include the following information, preferably in the order given below.

1. Name, Present Occupation, Business and Home Address, Phone and Fax Numbers, and SID Grade (Member or Fellow) of Nominee.

2. Award being recommended:
   Fellow*
   Jan Rajchman Prize
   Karl Ferdinand Braun Prize
   Johann Gutenberg Prize
   Beatrice Winner Award
   Special Recognition Award
*Fellow nominations must be supported and signed by at least five SID members.

3. Proposed Citation. This should not exceed 30 words.

4. Name, Address, Telephone Number, and SID Membership Grade of Nominator.

5. Education and Professional History of Candidate. Include college and/or university degrees, positions and responsibilities of each professional employment.

6. Professional Awards and Other Professional Society Affiliations and Grades of Membership.

7. Specific statement by the nominator concerning the most significant achievement or achievements or outstanding technical leadership which qualifies the candidate for the award. This is the most important consideration for the awards committee, and it should be specific (citing references when necessary) and concise.

8. Supportive material. Cite evidence of technical achievements and creativity, such as patents and publications, or other evidence of success and peer recognition. Cite material that specifically supports the citation and statement in (7) above. (Note: the nominee may be asked by the nominator to supply information for his candidacy where this may be useful to establish or complete the list of qualifications).

9. Endorsements. Fellow nominations must be supported by the endorsements indicated in (2) above. Supportive letters of endorser will strengthen the nominations for any award.

Send the complete nomination – including all the above material by **October 13, 2000** – to the Honors and Awards Chairman, Dr. Andras I. Lakatos, Society for Information Display, 31 East Julian Street, San Jose, CA 95112 USA; e-mail: sidawards@sid.org.

rejected (no form letters please). Please send these endorsements to me either in hardcopy or by e-mail (preferred) to the address stated in the accompanying text box. The Honors and Awards section of the SID Web site contains all this information along with the names of all previous award winners.

Last year the Honors and Awards Committee received a good selection of well-qualified nominees for the Fellow and Special Recognition Awards, but there were very few nominees for most of the major awards. I am especially appealing to you and urge you to nominate worthy candidates for all the major prizes as well as candidates for the Fellow and Special Recognition awards.

As I state each year: "In our professional lives, there are few greater rewards than recognition by our peers. For an individual in the field of displays, an award or prize from SID, that represents her or his peers worldwide, is a most significant happy and satisfying experience. In addition, the overall reputation of the society depends on the individuals who are in its 'Hall of Fame'.

When you nominate someone for an award or prize, you are bringing happiness to the individual and his or her family and friends, and you are also benefiting the society as a whole."

Thank you for your nominations in advance.

– Andras I. Lakatos, Chairman
SID Honors and Awards Committee

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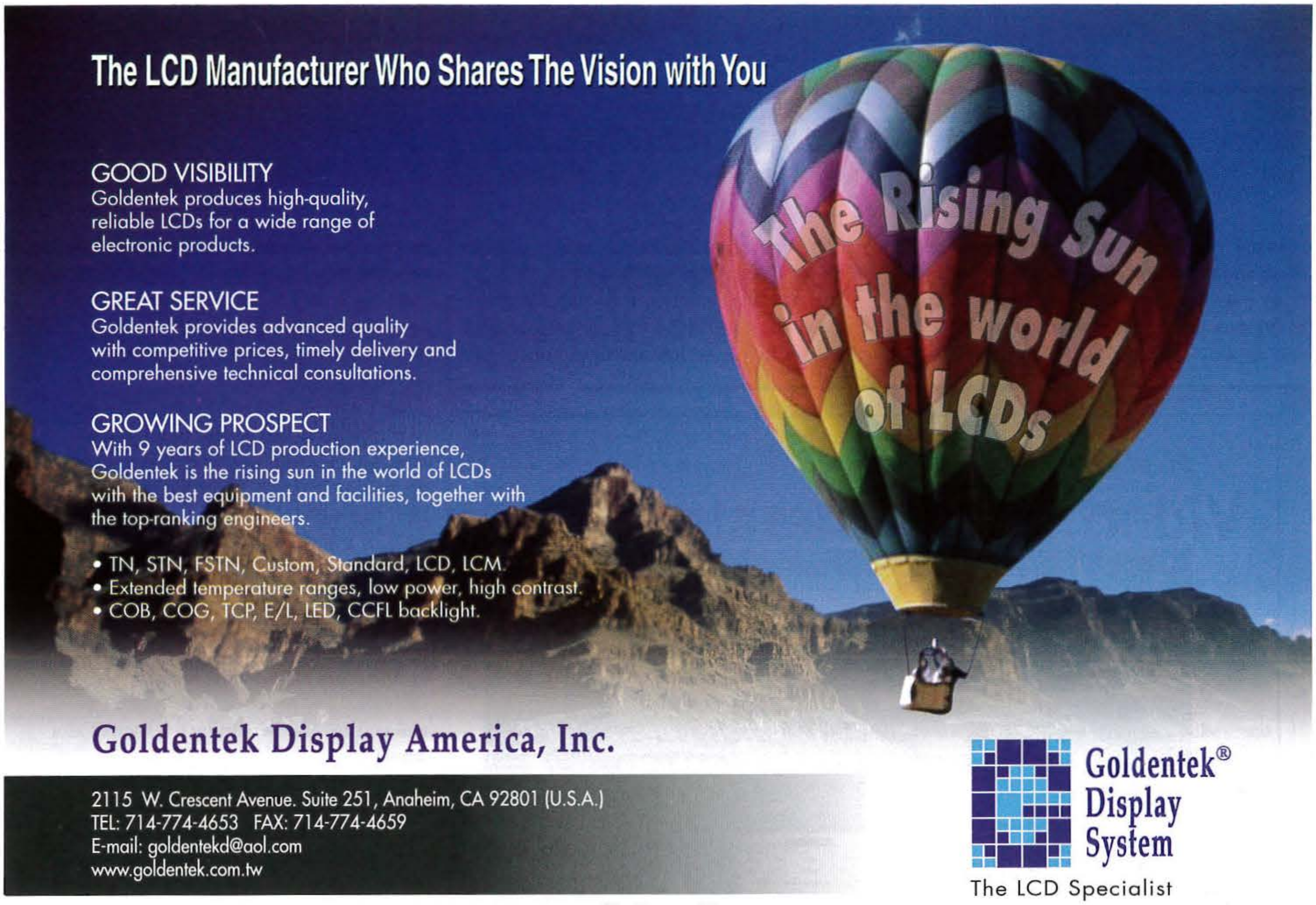

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SID Conference Calendar

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The 2000 International Display Research Conference (IDRC '00)

The 20th edition of the International Display Research Conference will be held at The Breakers Hotel, Palm Beach, Florida, September 25–28, 2000. This year's conference is comprised of papers from Asia, Europe, the U.S. and Canada. The presentations reflect the current thrust of flat-panel research on organic LEDs, virtual displays, and light valves on Si for projection, printing replacing vacuum processes, and reflective displays with color or multiline addressing.

25 SEPTEMBER 00

20th International Display Research Conference (IDRC '00)

PALM BEACH, FLORIDA
SEPTEMBER 25–28, 2000

• An international conference on display research and development aspects of:
– Display Fundamentals, Display Devices
– Hard Copy & Storage, Input Systems
– Integrated Devices and Applications
– Image and Signal Processing,
– Color Perception, Human Factors

6 NOVEMBER 00

Sixth International Conference on the Science and Technology of Display Phosphors

SAN DIEGO, CALIFORNIA
NOVEMBER 6–8, 2000

• An international conference on the future prospects of phosphors for:
– OLEDs – ELDs – FEDs
– CRTs – Plasma Displays
– PL Devices – LC Backlights

7 NOVEMBER 00

8th Color Imaging Conference: Color Science, Engineering, Systems & Applications

SCOTTSDALE, ARIZONA
NOVEMBER 7–10, 2000

• An international multidisciplinary forum for dialogue on:
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– Color Image reproduction and interchange
– Co-sponsored with IS&T

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110 ☐ Yes 111 ☐ No

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212 ☐ Engineering Systems (Evaluation, OC, Stds.)
213 ☐ Basic Research
214 ☐ Manufacturing / Production
215 ☐ Purchasing / Procurement
216 ☐ Marketing / Sales
217 ☐ Advertising / Public Relations
218 ☐ Consulting
219 ☐ College or University Education
220 ☐ Other *(please be specific)* ______________

3. What is the organization's primary end product or service? (check one)

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311 ☐ Electroluminescent Displays
312 ☐ Field-emission Displays
313 ☐ Liquid-crystal Displays & Modules
314 ☐ Plasma Display Panels
315 ☐ Displays (Other)
316 ☐ Display Components, Hardware, Subassemblies
317 ☐ Display Manufacturing Equipment, Materials, Services
318 ☐ Printing / Reproduction / Facsimile Equipment
319 ☐ Color Services / Systems
320 ☐ Communications Systems / Equipment
321 ☐ Computer Monitors / Peripherals
322 ☐ Computers
323 ☐ Consulting Services, Technical
324 ☐ Consulting Services, Management / Marketing
325 ☐ Education
326 ☐ Industrial Controls, Systems, Equipment, Robotics
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330 ☐ Oceanography & Support Equipment
331 ☐ Office & Business Machines
332 ☐ Television Systems / Broadcast Equipment
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334 ☐ Test, Measurement, & Instrumentation Equipment
335 ☐ Transportation, Commercial Signage
336 ☐ Other *(please be specific)* ______________

4. What is your purchasing influence?

410 ☐ I make the final decision.
411 ☐ I strongly influence the final decision.
412 ☐ I specify products/services that we need.
413 ☐ I do not make purchasing decisions.

5. What is your highest degree?

510 ☐ A.A., A.S., or equivalent
511 ☐ B.A., B.S., or equivalent
512 ☐ M.A., M.S., or equivalent
513 ☐ Ph.D. or equivalent

6. What is the subject area of your highest degree?

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611 ☐ Engineering, other
612 ☐ Computer / Information Science
613 ☐ Chemistry
614 ☐ Materials Science
615 ☐ Physics
616 ☐ Management / Marketing
617 ☐ Other *(please be specific)* ______________

7. Please check the publications that you receive personally addressed to you by mail (check all that apply):

710 ☐ *EE Times*
711 ☐ *Electronic Design News*
712 ☐ *Solid State Technology*
713 ☐ *Laser Focus World*
714 ☐ *IEEE Spectrum*

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