

Microdisplays based upon organic light-emitting diodes

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Microdisplays, some of which exploit the dense electronic circuitry in a silicon chip, are enabling a new wave of ultraportable information products, including headsets for viewing movies and cell phones with full-screen Internet access. This paper reports the approach to microdisplay development at eMagin Corporation. The requirements for microdisplays are reviewed, and the case is made that organic light-emitting diodes (OLEDs) are the best candidate transducer technology for meeting these requirements. A 1280 × 1024 (SXGA) monochrome OLED microdisplay is described as an example.

Introduction

The rise in importance of electronic displays over the last forty years has been a direct consequence of the explosive proliferation of computers of all sizes, from the large mainframes of the 1960s and 1970s to the small handheld systems of the late 1990s. Initially, displays based on neon discharges were used to display binary and decimal digits, but these quickly gave way to displays which exploited the cathode ray tubes (CRTs) developed for television. Because of the economies of scale afforded by the huge television market, the CRT still represents nearly half of the information display market in dollars, and more than half in terms of units.

In spite of the fact that the CRT is still the most economical technology for displaying 0.3–3.0 million picture elements (pixels), it has never been able to shed its most serious drawbacks of weight and volume. For this reason, even in the early days of television, engineers dreamed of making thin, light “flat-panel” displays that would capture the function of the CRT in a more attractive package, perhaps even one that would be easily portable. Unfortunately, the first major commercial flat-panel technology, based again on neon discharges, was not, when introduced, economically competitive with the CRTs it was intended to replace. As desktop displays, plasma displays (as they were then called) were too expensive and lacked the ability to render full color. For portable applications, they were too heavy and too inefficient.

Since the advent of the personal computer in the early 1980s prompted everyone to look for a way to make a portable version, display attention shifted to liquid crystal displays (LCDs), which already had gained a reputation, in watches, for low power demands and low weight. Early screen images produced on liquid crystal flat panels were grossly inferior to CRT images, even if the computers incorporating them were highly portable. In 1983, however, workers at Seiko-Epson produced a small, backlit liquid crystal display with color filters, and a thin-film transistor at each pixel site, that yielded for the first time a flat-panel display with the image characteristics of a color CRT [1]. Within five years, this technology had been developed to a point at which displays suitable for portable computers became feasible.

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Figure 1

Microdisplay headset designed for DVD (movie) viewing (Virtual Vision).

Although this active-matrix LCD technology was not, and is not, competitive in cost with CRT technology, the new function of portability was so highly valued that a major industry was enabled by its existence. The market for portable computers of various sizes is now in the range of \$50 billion per year [2]. Looking back, it is clear that a critical milestone for triggering the growth of the market was the ability to provide an image competitive with that of the CRT, after which cost became secondary.

In spite of their great success, even directly viewed flat-panel displays have their limitations as portable devices. For instance, if one wants to provide a large amount of information, i.e., a large number of pixels, it is necessary to use a large flat panel because of the limitations of the human visual system, especially in adults. But a large display is too cumbersome for use while walking. Also, with the convergence of information system technology and entertainment, exemplified by the DVD (digital versatile disk), creating a large-viewing-angle experience similar to that encountered in a cinema requires a very large flat-panel display.

The need for high information content and small size is the driving force behind the development of high-resolution microdisplays, by which we mean displays that are viewed

close to the eye, with the aid of lenses. As with flat-panel displays, microdisplays provide access to large amounts of information, but with another level of portability and convenience. As with flat-panel displays, they also have the potential of enabling huge new markets that do not require the displacement of an entrenched existing technology. This paper deals with the opportunities for microdisplays and a new technology approach to such displays, using organic light-emitting diode (OLED) emitters integrated onto silicon chips, in the context of portable or even wearable display systems.

Applications

Since the combination of a microdisplay and optics can produce a virtual image, it can appear to be a large screen



(a)



(b)

Figure 2

Wearable computer headset monitors by (a) IBM, (b) Virtual Vision.

at a great distance (for example, a 10-ft diagonal screen ten feet away) or a conventional monitor at desktop working distance (for example, a 19-in. diagonal screen at 20-in. distance). The image can be superimposed on the external world in a see-through optics configuration, or, with independent displays for both eyes, a true 3D image can be created.

There are a host of potential applications, starting with entertainment headsets (see **Figure 1**), potentially the highest-volume market. In this application, a two-display lightweight binocular headset provides the illusion of watching a movie on a cinema-sized screen. The user could be in the back seat of an automobile, on a train or airplane, lying in bed, or on a beach.

Another potentially large market is for use with wearable computers (**Figure 2**), ultralight portable systems for which a light, monocular microdisplay headset would provide the full capabilities of a CRT monitor or a liquid crystal flat panel. Thinking about the uses of a wearable computer, one imagines that all kinds of information could be available on an "anytime, anyplace" basis. Schedules, e-mail, documents, business reports, etc. could be reviewed anywhere, with complete privacy. While touring a warehouse or storage yard, one could, with a bar-code wand, bring up all of the relevant information about an item. Maintenance and repair personnel could have service manuals, even service videos, available for hands-free reference. If wireless capability is added, the whole world of the Internet becomes accessible.

Another potentially large market for microdisplays is the 3G (third-generation) cellular phone, or cell phone, in which all of the systems under consideration for introduction starting in the year 2001 will support wideband access to data and images, including Web pages. Since it has been forecast that most business-to-business transactions will take place over the Internet, a cell phone that provides Internet access will be as essential as a voice cell phone is today. This could be accomplished, as it is today, by reformatting Web pages for apportionment on small, low-resolution displays; however, it could be done by including in the cell phone a microdisplay viewer capable of showing the information unchanged (see **Figure 3**).

Markets that are smaller but still important include helmet displays for pilots and soldiers, capable of providing cueing, infrared images, maps, etc., and head-mounted displays for medical practitioners, showing X-rays, patient status, endoscopic images, etc.

All of these opportunities are made possible by a confluence of technological developments in silicon chip capability and display technology. On the silicon side, ever-decreasing feature sizes have led to a high level of functional integration on a single silicon chip. Display technologies have progressed both in terms of pixel addressing (from passive to active matrix) and operating



Figure 3

Concept drawing of a cell phone incorporating a microdisplay viewer.

voltage levels (from ~40 V in the mid-1980s down to less than 3 V today for LCD technologies). In addition, the introduction of a new, low-voltage emissive technology based upon organic light emitters has provided an alternative to liquid-crystal-based displays. Wireless access applications will experience a major impetus associated with the upgrading of cellphone networks.

Microdisplay requirements

While the markets for microdisplays have the advantage that one is not trying to displace an established technology, nevertheless the requirements for success are numerous and demanding. Some companies have already failed by trying to offer products for virtual-reality applications with resolution inferior to that generally available on desktops and in notebook computers. Thus, the first requirement is for a large number of pixels in a small package. While there are applications for a 320×240 format (QVGA), generally speaking 640×480 (VGA) pixels is the minimum desired for most applications, and there is significant interest in as many as 1920×1080 (HDTV) pixels. The largest part of the performance market would be satisfied by 800×600

(SVGA) or 1024×768 (XGA) formats, with display sizes less than 25 mm diagonal. To achieve these formats, pixel sizes would have to be in the 12- to 24- μm range.

As with flat-panel displays, the targets for image characteristics are set by the need to visually match the CRT, more precisely the computer monitor color CRT, which has significantly better capability than a TV CRT. This means that luminance should be at least 100 cd/m^2 , and contrast greater than 100:1. For outdoor applications with see-through optics that superimpose the display image on a bright natural environment, the luminance required may be as high as 3000 cd/m^2 , a level not typically achieved even by color CRTs. The most demanding pilot helmet displays require $30\,000\text{--}40\,000 \text{ cd/m}^2$ luminance, since they are viewed by reflection from a weakly reflecting clear plastic visor.

Typically, 256 gray levels are desired for each primary color, and the color gamut, or range, should match or exceed that of a standard color CRT. In order to match the CRT for showing video information, the rise and fall times for the microdisplays must be less than a few milliseconds.

Efficiency is always an issue for displays, but it is especially important for microdisplays that are to be used in handheld appliances or headsets for wearable products. To qualify for portability, a system must have a low weight (for instance, no more than 4–5 oz. for a headset). A major source of weight in autonomous electronic systems is the power source, typically a battery. A higher-efficiency system will minimize the power requirements and allow the use of a smaller and lighter battery. For example, a white OLED emitter with an efficiency of one lumen per watt (1 lm/W) will result in a filtered white color microdisplay that dissipates about 0.25 W (assuming a chip active area of 1 cm^2 and a surface luminance of 150 cd/m^2). Control and driving circuitry can add another 150 mW, depending upon the level of functional integration, leading to a 0.4-W total microdisplay subsystem power. This number is close to the high end of what is considered acceptable for a high-resolution (SVGA and above) headset (typically less than 0.5 W per display). Thus, 1 lm/W is a minimum design point for white OLED emitters. In the case of liquid crystal displays, this would mean that the combination of light source and light valve must provide an equivalent efficiency. In the case of reflective LC displays, beam splitters and at least one polarizer are frequently used, and their losses must be included. (The maximum optical throughput of a beam splitter is 50%. In practice, secondary effects due to diffraction and scattering reduce this quantity to around 40–45%.) When comparing OLED with reflective LC displays, it is necessary to use a common reference. A practical approach is to consider a typical monitor, similar to the

ubiquitous CRT computer monitor, and examine the efficiency for each technology in a complete system implementation. As discussed below, there is a high power penalty for color field-sequential displays once the electronic circuitry is taken into account, one that is proportional to the number of pixels in the display.

Lifetime requirements are highly dependent upon the application. For example, entertainment headsets need a lifetime to half luminance of more than 10 000 hours, at a luminance of about 150 cd/m^2 . Since white emitters have been shown to have lifetimes to half luminance of considerably more than 10 000 hours for initial luminances of $700\text{--}800 \text{ cd/m}^2$, this requirement can be met, even after accounting for the losses in color filters. Displays which may show fixed-pattern information require that luminance vary less than 2% over the useful life, in order not to show ghost images of a fixed pattern. This is a much more difficult challenge, especially given that the observed degradation follows very closely a stretched exponential functional form, i.e., $L \cong L_0 \exp(-\alpha t^{1/2})$, where L is the display luminance, L_0 is the initial luminance, and α is the experimentally determined lifetime constant.¹ For such applications, a screensaver may be needed, as is the case for CRTs.

Most interesting, and for some technologies most difficult, are the requirements that relate to the optics of a microviewer. For accessing large amounts of information and for creating a large-screen experience with a microviewer, a large viewing angle is necessary. For comfortable viewing even while wearing eyeglasses, a fairly large eye relief² is essential. Finally, a generous exit pupil³ is needed to ensure that the pupil of the eye is filled even as the eye rotates to use the large viewing angle and to ensure that some movement of the microviewer relative to the eye is not going to degrade the image. The latter is especially important when the headset is permitting hands-free activity, that is, when fine adjustments are not possible. **Figure 4** shows a schematic of a microviewer optical system for purposes of illustrating eye relief, viewing angle, and exit pupil (sometimes called “eyebow”). Actual magnifier optics would be more complex, but this schematic serves to illustrate the essential points.

For example, even though the iris of the eye is 3–7 mm in diameter, depending upon light level, the exit pupil must be 12–15 mm in diameter. A consequence of this is that a large cone of rays must be used from each image point, and if the luminance or contrast of the image varies with angle, the result will be a variation of the appearance of the image over the range of the exit pupil. For example, if the display were a liquid crystal display, there is a

¹ J. Chou, eMagin Corporation, private communication.

² Distance from the pupil to the first surface of the optical system.

³ Minimum diameter of the bundle of light rays emerging from the magnifier optics such that light from every point in the image is included.

well-known variation of luminance and contrast with angle in one direction, usually the vertical direction. The extreme rays at the top and bottom of the diagram would present a very different appearance of the display, such that as the eye rotates to look at the top, the display might lighten and lose contrast, while a rotation to the bottom would darken the display. If the eye is moved within the exit pupil, the effect is also obvious. While this phenomenon is not documented by makers of LCD microdisplay headsets, it is easily observed and privately acknowledged. If the display is Lambertian (i.e., it has a uniform appearance independent of angle), the appearance of the display in the microviewer will be independent of eye position and rotation. This is a difficult requirement, one which cannot be met by the commonly used twisted nematic liquid crystal displays, except where a small viewing angle is acceptable. More precisely, it is necessary that the appearance of the display be uniform (Lambertian) over the range of angles required to fill the viewing optics.

Existing technologies

Several technologies are amenable to the fabrication of displays with very small pixels, liquid crystals, thin-film electroluminescence, and organic light-emitting diodes. All involve transducers which are less than a few micrometers thick, and all exhibit negligible pixel-to-pixel coupling even at close spacings.

Liquid crystals can be used in a transmissive mode, as in a notebook computer display, where an active matrix of silicon or polysilicon thin-film transistors is formed on a quartz substrate to provide the control signals and where the light comes from a backlight, which might be a small fluorescent tube or an array of conventional light-emitting diodes (LEDs). Products of this type are on the market today in the NTSC⁴ (Seiko-Epson) and SVGA (Sony) formats. Because of the backlight and the inefficiency of color filters, the SVGA display modules are not efficient enough for true portable use.

Liquid crystals can also be used in reflective mode, in which the active matrix is formed on a silicon chip and the liquid crystals modulate the reflectance of light from an illumination system. Typically, color is provided by sequential illumination with light from red, green, and blue light-emitting diodes, at a frequency of 180 Hz or higher [3]. This approach has the advantage that the single-crystal active-matrix circuitry provides higher performance at a lower power than does polysilicon. Even so, the power efficiency is still low because of the sequential illumination requirements which, in effect, triple the required data bandwidth when compared to

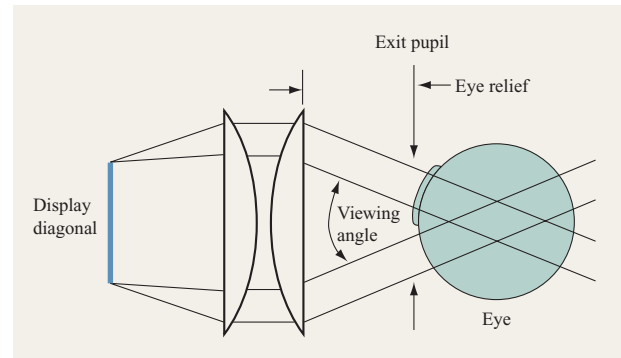


Figure 4

Schematic view of the optics of a microdisplay, illustrating the important design parameters.

non-field-sequential display technologies. Reflective microdisplays are available at the SVGA level (Colorado Microdisplay, Microdisplay Corp., InViso, Three-Five Systems Inc.). The displays manufactured by Kopin (QVGA and VGA), while operating in a transmissive mode [4], rely on a field-sequential approach for color. All frame-sequential color systems suffer additionally from the problem of color breakup, whereby any eye movement leads to a spatial separation of the three color images on the retina. This can be distracting and fatiguing, especially if the user is subject to vibration such as that experienced in a car, bus, or train.

Both liquid crystal approaches suffer from the viewing-angle problem described above, in which the appearance of the image changes with slight movements of the microviewer as well as changing across a wide-angle image.

Another technology which has been used to fabricate microdisplays is thin-film electroluminescence [5] (TFEL), wherein a thin film of ZnS sandwiched between two insulating films emits light under the influence of a high electric field of alternating polarity. In this case, the emitting structure is deposited onto a silicon chip containing the active-matrix circuitry. This approach can be used only where high brightness or high efficiency is not required, since the efficiency for color displays is very low. Also, the high voltages demanded by the TFEL technology (75–200 V) require special high-voltage silicon processes, which add greatly to the cost of the displays. Optically, the TFEL displays are well suited, because the emission characteristics are Lambertian, and yellow monochrome displays can be bright.

Advantages of OLEDs on silicon

The best match to the range of microdisplay requirements is achieved by the combination of OLEDs on silicon.

⁴ National Television Standards Committee (NTSC). This refers to the standard commercial television format with 480 active lines.

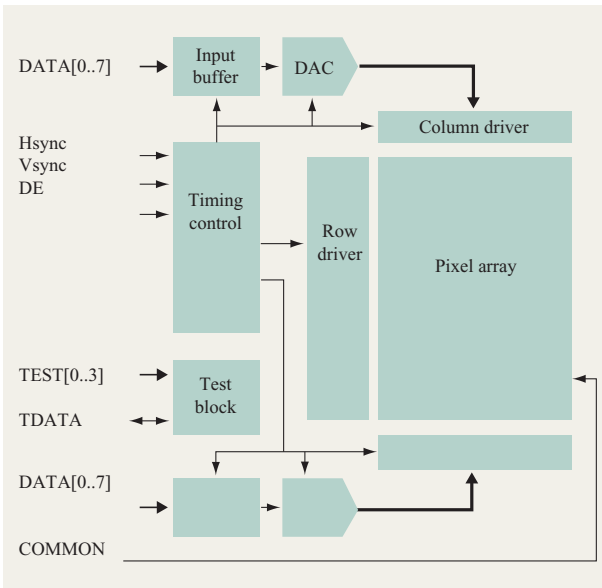


Figure 5

Block diagram of circuitry in a typical microdisplay chip with digital input. (DAC = digital-to-analog converter.)

OLEDs are efficient Lambertian emitters that operate at voltage levels (3–10 V) accessible with relatively low-cost silicon. They are capable of extremely high luminances ($>100,000 \text{ cd/m}^2$), a characteristic which is especially important for military pilot helmet applications, even though most of the time they would be operated at much lower levels. Luminance is directly linear with current, so gray scale is easily controlled by a current-control pixel circuit. OLEDs are very fast, with response speeds superior to those of liquid crystals, an important feature for video displays. Fabrication is relatively straightforward, consisting of vacuum evaporation of thin organic layers, followed by thin metal layers and a transparent indium–tin oxide layer. A whole wafer can be processed at one time, including a process for sealing, before the wafer is sawed into individual displays. Up to 400 small displays (QVGA format using a $12\text{-}\mu\text{m}$ color pixel pitch and a die size of $8 \text{ mm} \times 7 \text{ mm}$) can be produced from a single 8-in. wafer, including interface and driver electronics embedded in the silicon.

An additional efficiency advantage of OLEDs (or any emissive technology) over liquid crystal microdisplays is that the average level of light emission for video applications is about 25% of that required for a full white screen. Since backlit or frontlit displays must always supply enough light for a full white screen, an emissive display, such as an OLED-based display, which emits light only when required, therefore has a 4:1 advantage in actual power used for emission. Given the much higher

efficiency of the inorganic LEDs used to illuminate reflective or transmissive LC displays, the final efficiency gain of the OLED over these technologies is closer to 2:1 once the power required to support a field-sequential color addressing mode and the losses due to the use of polarizers, beam splitter, and diffuser have been taken into account.

Electrical requirements—General

The most difficult aspect of fabricating a microdisplay is getting the electrical control signals to so many picture elements in so small a space. For example, a monochrome 1280×1024 display requires a minimum of 2304 connections to the rows and columns in order to be able to write information to the display. Given that the perimeter is only about 55 mm (for $12\text{-}\mu\text{m}$ pixel pitch), wire bonding or tape bonding of external circuits is out of the question. Also, external circuitry for driving the rows and columns would add unacceptably to the bulk of the microviewer module.

The only practical approach is to integrate the circuitry for driving the display on the same substrate. This means that in order to maintain a small number of interconnections, the chip must accept data serially and transfer it to the pixels one row at a time. One of the basic choices is whether the data is to be in digital form (in which case the chip must incorporate digital-to-analog converters) or in analog form, which can be transferred directly to the pixels. For all of the technologies discussed above, with the exception of ferroelectric LCDs, the pixels are analog; i.e., the luminance is controlled by the magnitude of a voltage or a current. At this level, the circuitry is no different from that used to control any active-matrix display; the difference is that it is all on one chip, a fact that is made possible by the small electrical loads on the circuits compared to those that would be encountered in a notebook display, for example, or a desktop display. The key challenge is the speed at which the circuits must operate, this being roughly proportional to the number of pixels in the display. **Figure 5** shows a block diagram of the circuitry required for a digital input microdisplay.

There are two basic approaches to matrix display operation: passive and active modes (a third technique is the scanned display). The passive mode relies on data and select drivers to provide the desired information at the correct location in the pixel array. The amount of time spent at each pixel for converting the electrical information into a light modulation is therefore inversely proportional to the number of pixels in the array. More precisely, because of the use of parallel addressing techniques, the addressing time is inversely proportional to the number of rows in the matrix. It can quickly be seen that this addressing mode cannot practically be used

for video-rate high-information-content flat-panel displays (those of formats greater than QVGA color). While dual- or quad-scan techniques⁵ have been used for direct-view LCDs, essentially for cost reasons, the resulting performance has always been compromised, frequently exhibiting crosstalk and response-time artifacts.

A scanned display uses only one line or column of information and an electromechanical system that moves this line perpendicularly to create a virtual image plane. The inherent advantage is that the display substrate itself requires only one line (or column) to work, making it very small and potentially inexpensive. The scanning mechanism can be a moving mirror or movement of the image source itself. The first commercial concept was introduced in the early 1990s as the Private Eye (fabricated by Reflection Technologies Inc.); it consisted of an LED line array and a moving mirror (actuated by a piezoelectric transducer). A more recent approach, pioneered by MicroVision, uses lasers to imprint the image directly onto the retina or onto an intermediate image plane. Both LEDs and lasers have very high peak luminance and good efficiency, enabling such an approach. However, since the realization of these display systems is a significant challenge, only one company (MicroVision) is still actively pursuing this path.

Popularized by LCD flat panels, the active addressing mode places a storage element at each pixel cell. The benefits of this approach have already been demonstrated with notebook (and now desktop) flat-panel displays. While its implementation requires additional substrate processing, it is now an accepted standard, and its price premium over passively addressed displays is no longer the barrier it once was. Combined with a line buffer⁶ and a vertical-stripe color pixel arrangement, this mode maximizes not only the time a pixel has to convert electrical data to light-modulated information, but also the time it takes to transfer the source information (from a computer or other video generator) to the pixel storage element. The net result is a bandwidth (and thus power) requirement reduction as well as a widening of the substrate technology performance tolerance.

The importance of this last statement comes to light when one looks at the technologies available for microdisplay active-matrix fabrication. Two of them are the dominant choices today: crystalline and polycrystalline silicon. Both have advantages and drawbacks; the

application usually dictates which one is the best compromise.

Polysilicon processes have been improved greatly over the last decade, and the technology is now becoming a mainstay of the direct-view LCD display business. It has been and still is used for microdisplays, mostly transmissive liquid crystal cells. Compared to crystalline silicon, polysilicon scales up relatively well and uses cheaper substrates, providing a significant manufacturing cost advantage. Until very recently, polysilicon was limited in terms of operating frequency and minimum feature size. This led implementers to use it for relatively low-information-content displays such as NTSC or QVGA formats. Seiko-Epson, Sony, and Sanyo are the leading polysilicon miniature display manufacturers. The limitations in bandwidth also drove the selection of an analog interface and signal processing. It has proven easier to implement a sample-and-hold stage than a high-speed digital shift register using polysilicon. Even so, most implementations today rely on parallel analog inputs (6 to 12 for color displays).

Sony recently introduced an SVGA polysilicon microdisplay that is likely the highest level of integration this technology has seen in a commercial form to date. However, the minimum feature size is still large, resulting in a very low display fill factor (ratio of transmissive versus opaque areas of the pixel cell), and thus a power consumption inadequate for practical portable systems. This limitation also prevents a higher level of functional integration, a desired characteristic for a lightweight display that can serve a wide range of applications (ranging from text to animated color graphics or even video imagery).

Crystalline silicon, on the other hand, offers the designer access to a high level of integration, as well as high performance from the standpoint of both frequency and power.

Clearly, CMOS is the preferred technology for high-information-content microdisplays designed for portable systems. It can accommodate both analog and/or digital inputs, offers a well-established infrastructure that is accessible, and does not require the display developers to make extraordinary capital investments.

These advantages have resulted in the active development of silicon-based microdisplays by several companies such as Colorado Micro Display, The Microdisplay Corporation, Kopin, DisplayTech, Planar Systems, and others. The advances in CMOS processes far exceed the requirements of the display technologies themselves. Sometimes this may even result in drawbacks because of the fast obsolescence of older (three- to five-year-old processes are considered ancient) and higher-voltage processes. Indeed, most display technologies lag behind advances in integrated circuits with respect to

⁵ In a dual-scan display, the display is split into two vertically, effectively doubling the number of columns but reducing their length and electrical load by a factor of two. While this requires double the number of column drivers, it enables a faster addressing mode and has been used extensively with passive-matrix LCDs. A quad-scan display is a dual-scan display with a further split in the horizontal direction, doubling the number of row drivers while reducing the display row load by a factor of two.

⁶ A memory used to store an entire line of video information with a serial data input and as many outputs as there are memory cells.

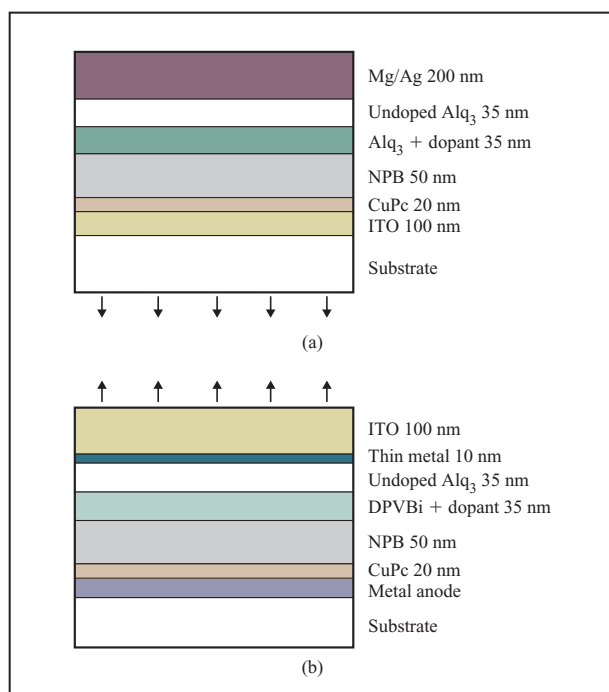


Figure 6

Schematic rendering of OLED stacks: (a) Down-emitting stack (green emission); (b) up-emitting stack (white emission).

voltage levels. This has placed constraints on material developments, such as a reduced voltage swing for LCD microdisplays, that have delayed product introductions. Furthermore, there is often a misconception concerning the amount of functionality that can be integrated within a microdisplay. The transducer technology dictates a minimum operating voltage level. This in turn places a lower limit on feature sizes, which places an upper limit on the number of functions one can add to a microdisplay silicon die without adverse economic consequences. Many of today's highly integrated circuits are designed with 0.25- or 0.18- μm design rules. These circuits do not operate above 2.5 V, and are not readily compatible with many of today's display technologies, be they mature or in development. Indeed, techniques to increase the operational voltage of circuits have been developed for active-matrix LCD driver ICs (notably by Vivid Semiconductor, now part of National Semiconductor). However, they still require a large amount of chip surface and therefore are not practical at the integrated pixel array level. As a result, the high levels of integration that are publicized for system-on-a-chip (SOC) or other leading-edge integrated circuits are not easily available to the microdisplay designer. Further advances in reducing display technology voltage requirements are needed.

Another aspect of silicon processes must be taken into consideration by the display designer, whether the signal processing is done in the digital or the analog domain. While not all display transducers are analog (FLCD,⁷ EL), the most popular, LCD, is. Gray levels can be rendered digitally (via pulse-width modulation), continuously (via amplitude modulation), or by a combination of both. From a circuit designer's standpoint, a higher level of physical integration can be realized with digital-only functions. Analog designs almost never use the minimum design rules, primarily because of on-chip device matching, which improves with larger physical structures. Analog designs are also more demanding and take longer to implement. They require a higher level of device characterization than their digital counterparts. Also, analog designs typically rely on resistors, which are fabricated with a second polysilicon layer. This requires a different process, more expensive and not as widely available. Several companies have realized this and have developed analog blocks compatible with logic processes. But for the display designer whose transducer is analog, the need to understand the silicon process behavior has not disappeared. High-performance displays are becoming the norm rather than the exception; 256 gray levels per color is considered the minimum entry point (today's video adapters, such as those fabricated by ATI and Matrox, typically go up to 10 bits per color).

Finally, the surface conditions of the integrated circuits must be compatible with the display technology. This is not automatic for all display technologies, and some process development has been required.

The display developers are thus in an interesting situation: In order to leverage the full potential of silicon processes, they have to refine their technology at the same rate, or accept some limitations and split their designs into more than one integrated circuit. The requirements of wearable/portable applications contribute to making this a system-level challenge. This will ultimately determine which display technology offers the best compromise.

Electrical requirements—OLED

Critical to the performance of the microdisplay chip is the circuit which controls the luminance of each pixel. To understand the electrical requirements here, we need to review some of the basic facts surrounding OLEDs.

Organic light-emitting diodes were invented by C. W. Tang and S. A. Van Slyke [6] of Kodak, who found that p-type and n-type organic semiconductors could be combined to form diodes, in complete analogy to the formation of p-n junctions in crystalline semiconductors. Moreover, as with gallium arsenide and related III-V diodes, the recombination of injected holes and electrons

⁷ FLCD: ferroelectric LCD.

produced light with very good efficiency. In contrast to the difficult fabrication of III-V LEDs, where crystalline perfection is essential, organic semiconductors can be evaporated as amorphous films, for which crystallization may be undesirable.

The prototypical OLED, which is used in consumer products today by Pioneer Corporation, is shown schematically in **Figure 6(a)**. Indium-tin oxide (ITO), which is transparent and also has a high work function (~ 5 eV), is sputtered onto a glass substrate as an anode contact for the injection of holes. A thin layer (20 nm) of copper phthalocyanine (CuPc) serves to facilitate the injection of holes by presenting a low barrier (i.e., there are states available not much deeper than 5 eV). The CuPc layer is followed by a layer of naphtha phenyl benzidine (NPB) about 50 nm thick, known as the hole transport layer (HTL). An emitting layer is next, consisting of 35 nm of tris(8-hydroxyquinolato)aluminum doped with a fluorescent dye such as Coumarin 540. An additional 35 nm of Alq₃ serves as the electron transport layer (ETL). Finally, electrons are injected from a low-work-function cathode. After the ITO layer, all of the layers are deposited by thermal evaporation. When current is passed through the organic stack, very bright green emission is obtained, with a quantum efficiency of about 10–12 cd/A and a luminous efficiency of about 4 lm/W at 2000 cd/m². **Figure 7** shows typical luminance–voltage, current–voltage, and spectral characteristics for such a device.

For use on top of a silicon chip we modify the stack, starting with a metal anode with a high work function and ending with a transparent cathode, followed by a layer of transparent ITO. We also change the active layer to make it a white-light emitter. We do this by using a diphenylene-vinylene (DPV)-type blue-green emitter, which is co-doped with a red dye to yield a white spectrum [7]. This stack is shown as **Figure 6(b)**. Typical L – V and I – V curves for a white emitter as well as its spectrum are given in **Figure 8**.

Even though an OLED microdisplay on silicon may have millions of subpixels, the OLED formation can be rather simple, because the complexity is all in the substrate. **Figure 9** shows schematically the cross section of a device. For each subpixel, corresponding to a red, green, or blue dot, there is a small electrode pad, possibly $4\ \mu\text{m} \times 14\ \mu\text{m}$, attached to an underlying circuit that provides current. The OLED layers can be deposited across the whole active area, using shadow masking in the evaporator. This includes the cathode, which is common for all pixels. This simple approach is made possible by the fact that the materials are not good lateral conductors, so the very thin organic films cannot shunt current from one subpixel to another. With such thin structures, light also does not leak into adjacent pixels, so contrast is maintained even between neighboring pixels.

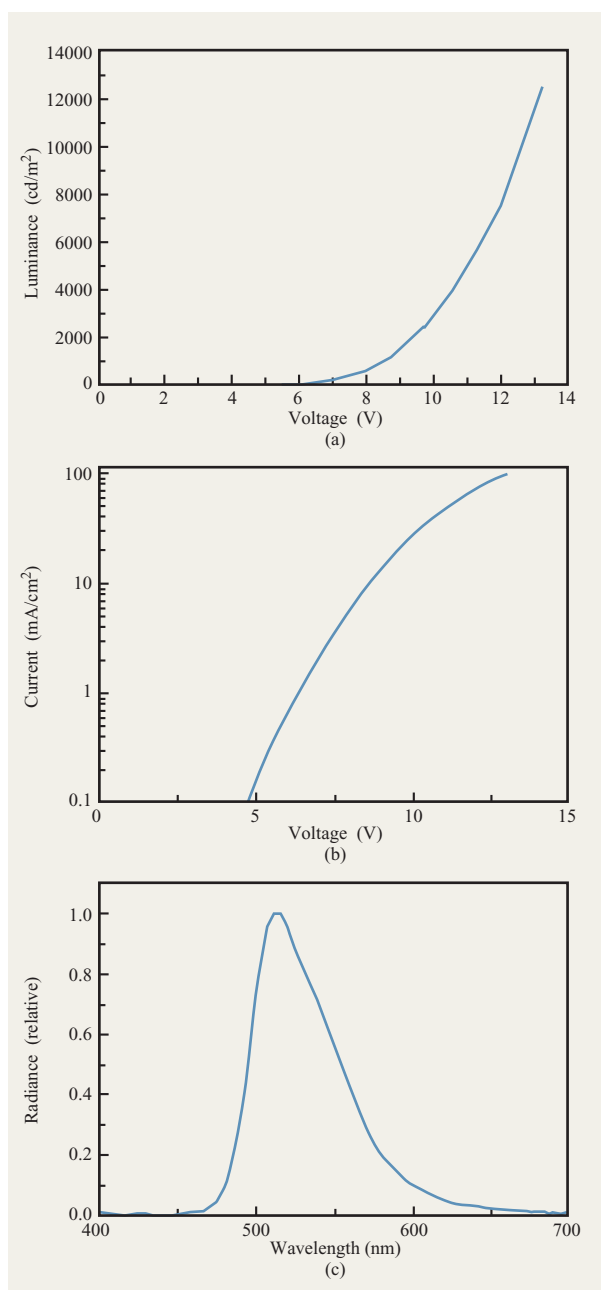


Figure 7

Electro-optical characteristics of a typical down-emitting green OLED: (a) Luminance–voltage variation; (b) current–voltage variation; (c) spectrum.

An important part of the wafer process is to ensure that the surface onto which the organic materials are to be deposited is smooth and flat. Because the layers are so thin, any roughness of the substrate could lead to nonuniform thickness in the organic layers, or even short circuits between anode and cathode. Fortunately, many

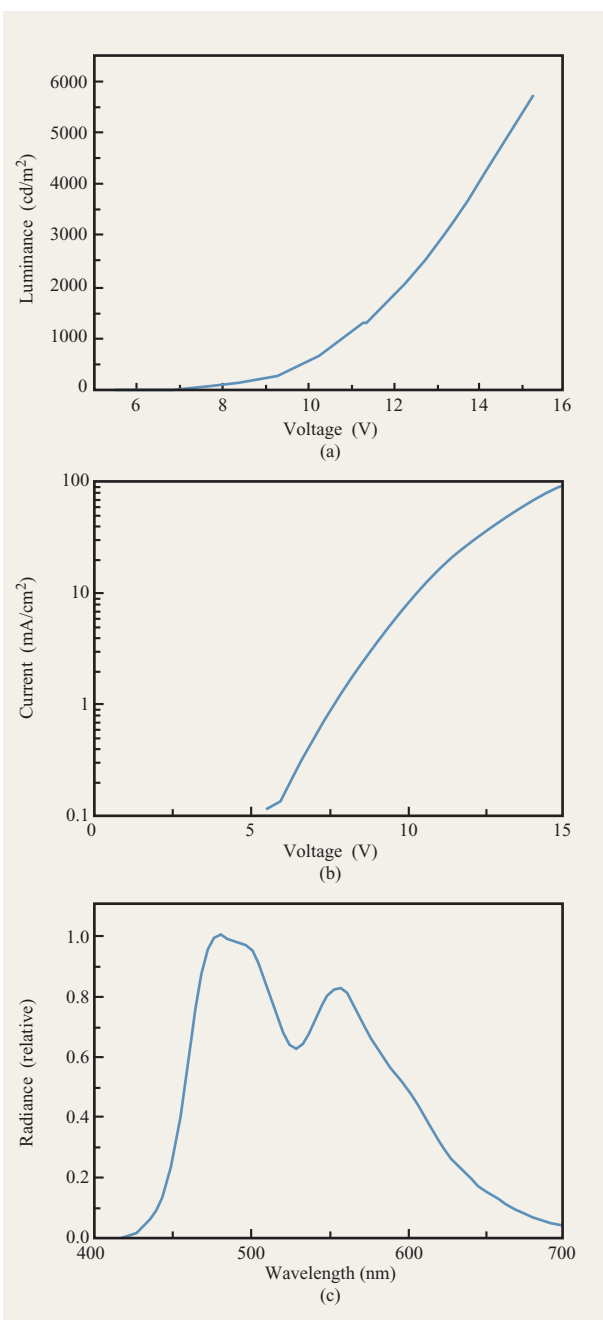


Figure 8

Electro-optical characteristics of a typical up-emitting white OLED: (a) Luminance–voltage variation; (b) current–voltage variation; (c) spectrum.

silicon foundries have developed such processes, so that their lithographic exposure systems can focus uniformly on a smooth, flat surface.

Figure 9 also illustrates the preferred way of producing color in microdisplays, which is by using color filters or

color conversion materials (CCMs). The filters, which are identical to those that are used in liquid crystal displays, can be used in conjunction with the white emitter described above to give a well-balanced color display. Each filter, of course, absorbs about two thirds of the light, so a more efficient approach is to use CCMs [8], whereby light from a blue emitter can be converted to green or red by absorption and re-emission. In this system, less than half of the light is lost, provided the CCMs are efficient.

OLED devices are very sensitive to moisture, which attacks the cathode materials; to a lesser degree, they are sensitive to oxygen, which can potentially degrade the organics. For this reason they must be sealed in an inert atmosphere after fabrication and before being exposed to ambient environmental conditions. OLEDs on silicon can be sealed by soldering a metal flange with a glass window directly to the surface of the silicon wafer (which is covered with insulating silicon dioxide). Properly done, such seals show no signs of moisture penetration after more than one year of environmental testing. **Figure 10** shows a packaged display with the metal flange cap. Other sealing materials, for example epoxy resins, can be used if an adequate amount of desiccant is provided inside the seal to absorb any moisture penetrating the epoxy. Also, thin-film hermetic seals are under development and show promise of eventual success, in which case the metal-sealed cap may be eliminated and replaced with a multilayer transparent thin-film barrier deposited over the OLED device before its exposure to ambient.

Electrical requirements—OLED pixel circuit

The critical part of the chip design which distinguishes chips for OLEDs from chips for liquid crystal displays, for instance, is the pixel, or subpixel, circuit. As we have indicated, this circuit must provide a constant current to the OLED device, but the magnitude of the current must be controllable over a range of more than 100:1 in order to allow for high-contrast images. To see what this means in terms of actual quantities, let us consider a color display for which the target white luminance, on an area basis, is 150 cd/m^2 , i.e., about the same as a typical desktop monitor.

The current source is one of the two critical components of the pixel cell. Its design is set by the actual pixel current requirement. This in turn is derived from the target luminance, the OLED efficiency, the color filter transmission (when used), the relative and absolute areas of the color subpixels, and the duty cycle of the pixel.

Let us consider an SVGA active matrix with a $15\text{-}\mu\text{m} \times 15\text{-}\mu\text{m}$ pixel. We further assume an active-matrix design, which results in a quasi-dc mode of operation for the pixel. Color is generated from a white emitter combined with individual color filters of equal area.

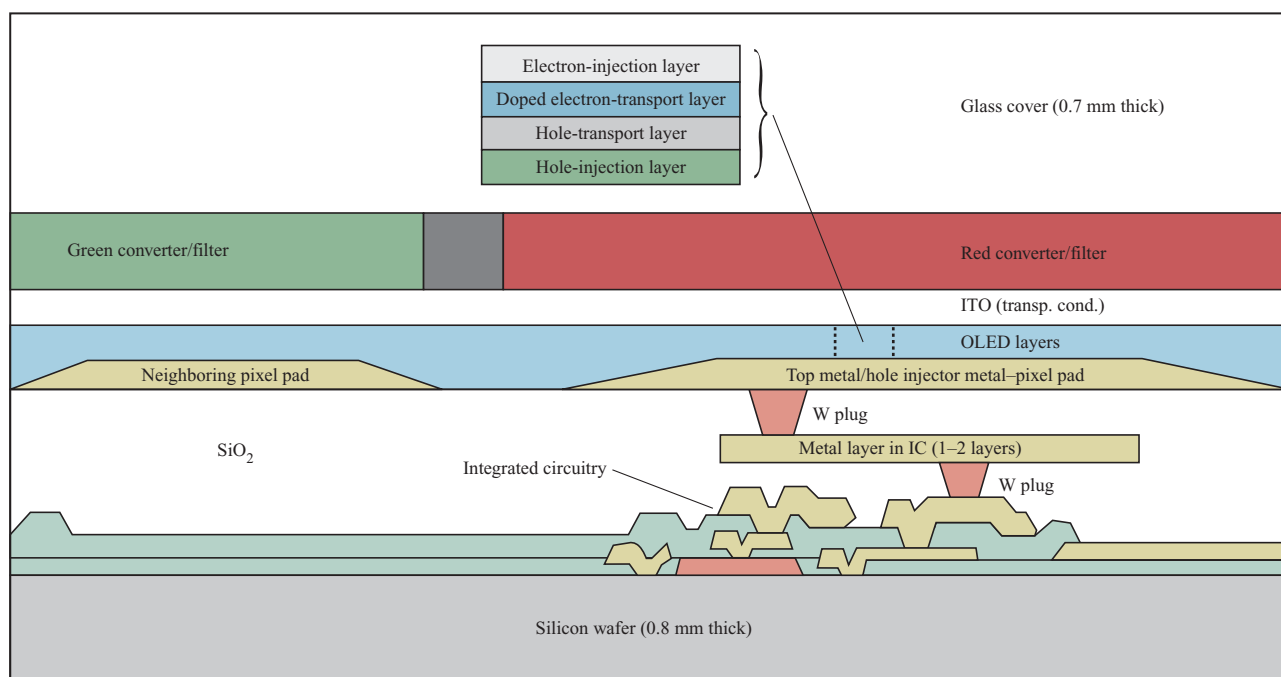


Figure 9

Schematic cross section of an OLED-on-silicon microdisplay.

The white luminance is the weighted sum of the primary red, green, and blue luminances. Knowing the transmission of the color filters, one can determine the emitter luminance requirement. In our example, it comes to 680 cd/m^2 at the emitter surface.

The next step is to calculate the effective emissive area. For process reasons, the emissive area of the pixel is smaller than the array pixel pitch. For transmissive technologies, this is referred to as the fill factor. A practical fill factor for a color OLED microdisplay is 65%. This leads to an effective emitter luminance of approximately 1050 cd/m^2 .

As indicated above, the OLED luminance is directly proportional to its current density. Given a 4-cd/A efficiency and a total emissive area of 0.70 cm^2 , the maximum current per subpixel comes to about 20 nA , or 28.8 mA total of OLED current.

The pixel current is therefore quite small, even from an integrated circuit standpoint. It also highlights the power efficiency of OLED and its suitability for microdisplay applications. Nonetheless, the control of this small current requires careful circuit design and process capability considerations.

The second most important component of an active-matrix OLED display is the storage element. Even though OLED is current-driven, the most practical way to store

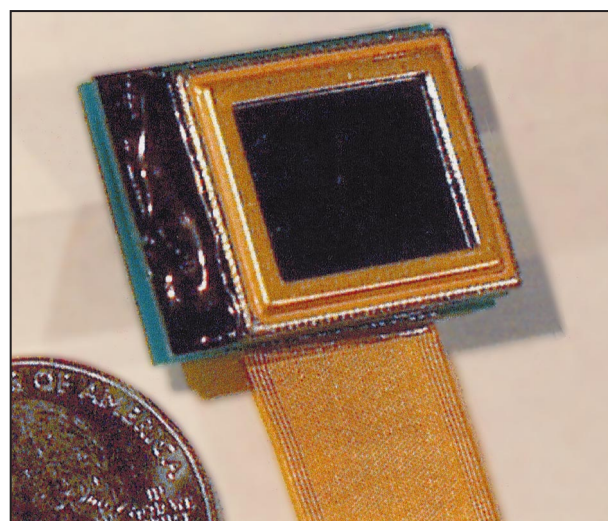


Figure 10

Packaged OLED-on-silicon chip with hermetic metal flange-type seal.

an electrical signal in an integrated circuit is to use a capacitor. Fortunately, a MOS transistor is a fairly good voltage-to-current converter, when driven properly. The small area of the pixel is in direct conflict with the typical

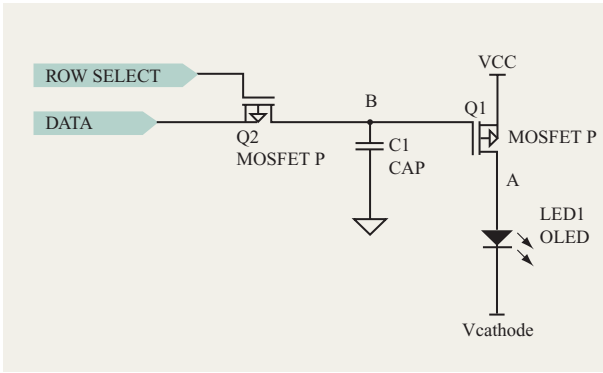


Figure 11

Electrical schematic of pixel circuit for an OLED-on-silicon microdisplay.

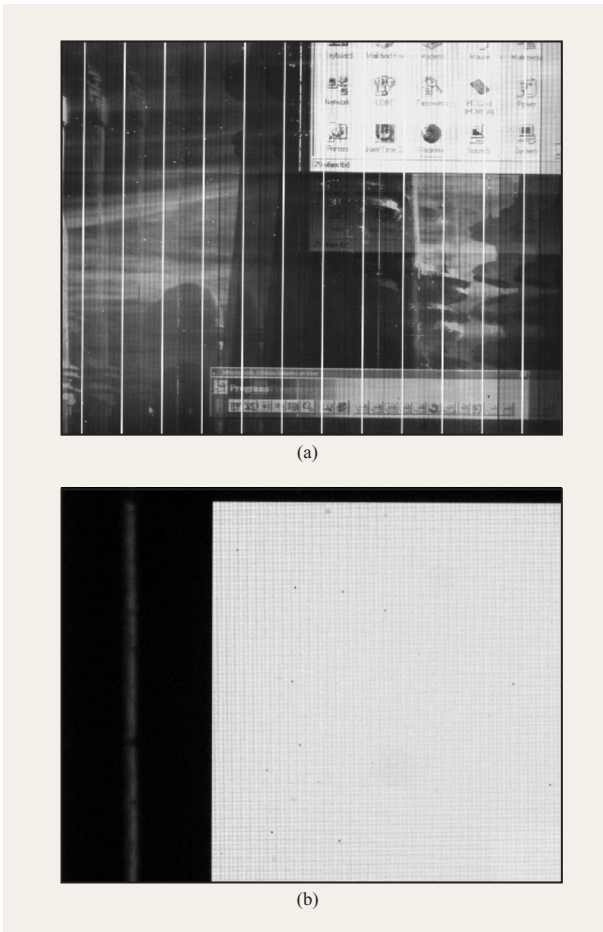


Figure 12

Photographs of an SXGA OLED-on-silicon microdisplay: (a) Video image; (b) all pixels on.

Table 1 OLED SXGA microdisplay specifications.

Format	1280 × 1024 pixels
Pixel aspect ratio	Square
Pixel pitch	12 μm
Viewing area	15.36 mm × 12.28 mm
Peak luminance	>600 cd/m^2
Chromaticity	Green (535-nm peak)
Gray levels	256
Contrast ratio	100:1 (Intrinsic)
Uniformity	>85%
Viewing angle	>160° both axes
Refresh rate	60 Hz or higher
Power consumption OLED	420 mW (@ 1000 cd/m^2)
Power consumption IC	500 mW (@75 Hz refresh)
Analog supply	−10 to +12 V
Logic supply	5 V dc
Data interface	Parallel digital (two bytes per clock)

requirement of a storage capacitor that it be as large as possible. Again, the benefits of CMOS technology provide some help by providing the designer with a very thin oxide (the gate oxide) that can be used to implement the storage needs. The circuit designer, however, still has the challenging task of completing the cell design with addressing switches while minimizing noise and leakage and providing adequate pixel-to-pixel uniformity.

A schematic diagram of a basic active-matrix OLED pixel cell is shown in **Figure 11**. In this configuration, all emitting devices share a common cathode to which a negative voltage bias is applied. This bias is set to allow the full dynamic range. Since the output transistor has a limited voltage capability, depending upon the silicon process used, it is important to have a steep variation in the OLED of luminance versus voltage, so that a large variation in luminance, e.g., 100:1, can be achieved for a voltage swing of 4 V or less.

SXGA monochrome display

An example OLED-on-silicon microdisplay is a 1280 × 1024 (SXGA) monochrome display with monochrome white 12- μm × 12- μm pixels. As indicated in the block diagram of Figure 5, this display has digital input, with 8-bit on-chip digital-to-analog converters. The specifications for the display are summarized in **Table 1**. Samples have been fabricated which meet the specifications in terms of luminance and efficiency, confirming the successful integration of OLED and silicon. The fabrication was carried out in a multichamber cassette-to-cassette vacuum system in which ten wafers can be loaded and coated with all of the films described earlier without exposure to atmosphere. The cassette

is unloaded directly into a glove box with an inert atmosphere, where the displays are sealed prior to removal from the glove box for sawing into individual displays. Connections to the chips are made by wire bonding.

Figure 12(a) shows a photograph of a displayed image. Unfortunately, the silicon circuitry has both logic errors and nonuniformities, which combine to give an image that is still far from ideal. The OLED array, however, is remarkably uniform, as can be seen in the photograph of **Figure 12(b)**, which shows the display fully on. It is expected that one more design pass on the silicon will at least eliminate the logic errors. The nonuniformities may require changes in the chip layout to reduce parasitic resistances, which were not well accommodated by the design system.

Summary

Microdisplays have the potential for creating new opportunities for ultraportable digital appliances and entertainment products. Organic light-emitting diodes offer the best technological approach to providing the viewing characteristics of a CRT in a small, light, power-efficient microdisplay module. The current status of this approach is that feasibility has been established, and manufacturing tooling has been developed. All that remains to be done is the fine-tuning of silicon circuitry designs for best performance, and the mechanical integration of color filters for full color capability.

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