MICRODISPLAYS move outside THE BOX

ILLUSTRATION BY STUART BRADFORD

Micromirrors, liquid crystals, and OLEDs each have strengths and tradeoffs for use in tiny displays.

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Microdisplays are used in business projectors, rear-projection TV, and the near-to-eye (NTE) viewers found in cameras and video headsets. These displays are compact picture-quality active-matrix electronic displays that present an image that must be magnified for a viewer to appreciate its full resolution. A number of technologies can be used to create microdisplays. The three main approaches of interest to microdisplays are electroluminescent, liquid-crystal, and micro-electro-mechanical-systems (MEMS) technologies. Due to space constraints, we're limiting this tutorial to microdisplays that use a complementary metal-oxide semiconductor (CMOS) as the active matrix substrate: the digital micromirror device (DMDs), liquid crystal on silicon (LCoS), and organic light-emitting diodes (OLEDs).

Active-matrix addressing is a form of multiplexing used to distribute a video signal over a high-resolution display with low cross-talk. Large-area active-matrix displays are built on glass substrates with thin-film-transistor (TFT) circuits. For very compact displays, CMOS has several advantages. The small circuit features allow for compact displays with pixel dimensions of less than 10 µm, and they are more efficient and suffer less manufacturing variation than TFT on glass. In addition, mainstream CMOS batch-processing techniques can fabricate wafers containing many microdisplays, and designers can integrate driver circuits and data processing onto the microdisplay chip to reduce the number of connections to the display.

The constraints regarding flatness and optical properties for CMOS used in microdisplays are more stringent than those required for conventional CMOS. In the case of LCoS technology—the most mature of the three CMOS technologies we discuss—several CMOS foundries have developed custom variants of standard processes that offer properties such as enhanced flatness, highly reflective top metal layers, and microfabricated posts for cell-gap spacing (see ***oe**magazine*, February 2001, page 22). DMD wafers have the mechanical-switching structures microfabricated directly on top of the conventional CMOS circuitry.

OLED, LCoS, and DMD

OLED technology is a relatively recent discovery but is attractive because it is blessed with low-voltage requirements, Lambertian emission, and fast response. The light emission from an OLED microdisplay is currently well below projector requirements, though in the future it may be possible to replace the 5-inch display in a CRT projection system by OLED devices of similar size.

OLEDs can be made either from small molecules or polymers (see figure 1). Small molecule OLEDs are based upon aluminum tris (8-hydroxyquinoline) and are created by vapor deposition (see ***oe**magazine*, February 2001, page 18). Light-emitting polymers are deposited in solution by spin coating for blanket coverage or by inkjet printing for patterned coverage (see ***oe**magazine*, June 2002, page 14).

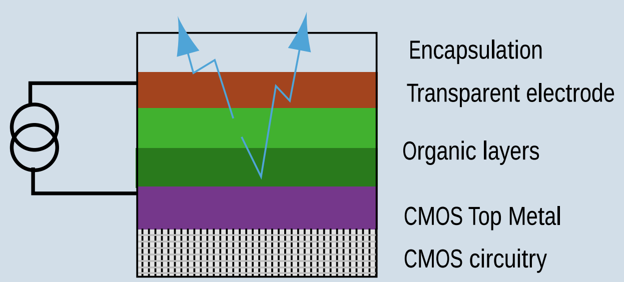


Figure 1 In each pixel of an OLED microdisplay, the light-emitting organic layer is sandwiched between the CMOS circuitry and the top electrode, with additional organic layers such as 3,4-polyethylene-dioxythiophene polymer included to enhance performance .

Making a monochrome OLED microdisplay is relatively straightforward, simply requiring a blanket deposit of the OLED material. To create color displays, one can blanket-deposit white-emitting material with patterned RGB color filters or blanket-deposit blue-emitting material with patterned RGB color converters. One could also pattern red-, green-, and blue-emitting materials, although this would be challenging, given the small dimensions of microdisplays.

The liquid-crystal configurations used in LCoS displays are restricted by the reflective geometry (see figure 2 on page 30), plus the demands of high throughput efficiency and contrast ratio. Developers favor a reflective version of the twisted nematic cell or the tilted vertical aligned cell. The cells function as analog polarization modulators, in which the reflected optical polarization depends on the applied voltage. Throughput efficiency of about 80% is determined by enhanced aluminum reflectivity and pixelation as indicated in figure 2. If the space between pixels is black, then the reflective area is reduced by the aperture ratio. If the pixel electrode gap is made by reflecting dielectric coatings, the aperture loss is recovered and driven by fringe field modulation. This approach also reduces diffraction loss.

The response speed of LCoS cells is about 10 ms at room temperature and falls as the temperature rises, which turns the elevated internal temperature of a projector into an advantage. Manufacturers can fabricate displays with a nematic cell gap as small as about 1 µm (i.e., the thickness of the liquid-crystal layer) when a response time faster than 1 ms is essential. Ferroelectric liquid crystals have a much faster response (less than 0.1 ms) in a binary off/on switching mode. Because liquid-crystal materials absorb little light, they can be used in high-power projectors. Pixel dimensions are limited by the voltages and circuit complexity required for the liquid crystals; currently, 10-µm pixel devices are in production, and 8-µm devices are proposed.

In the micro-machined DMD, each 13.7-µm pixel mirror is driven by electrostatic forces to the binary on-state (rotated +12° from normal) or the off-state (rotated –12° from normal), deflecting light in or out of an exit aperture (see figure 3 on page 30). The on/off contrast ratio is limited by diffraction and light scattering, which are minimized by designing mirror rotation in the diagonal plane of the pixel. In the packaged device, a glass window encapsulates the MEMS. Pulse-width modulation allows the device to produce shades of gray. The overall pixel response speed is about 15 µs, but the 2-µs optical transition time facilitates 14-bit grayscale precision at 60-Hz video frame rate. The device throughput efficiency of less than 70% is determined by aluminum reflectivity, pixel-to-aperture ratio, diffraction, and timing.

black and white in color

Full-color imagery can be achieved with red, green, and blue pixels, but requires three times as many pixels as a monochrome display for the same spatial resolution. For OLEDs, the easiest method of making a full-color display is to fabricate color pixels. Red, green, and blue images can be optically superimposed. Alternatively, each pixel can flash red, green, and blue fast enough for tristimulus response. In such a field-sequential-color (FSC) display, the monochrome pixel count is preserved but the required writing speed increases. Eye motion disturbs registration of the color fields on the retina, however. Attenuating such “color breakup” so that the time separation of the colors is not perceived requires FSC rates well beyond 180 Hz. To achieve 24-bit color, each primary color must have an 8-bit gray scale.

A simple projection system incorporates dichroic mirrors, polarizing beam splitters, and LCoS polarization modulators. Designers enhance efficiency and contrast ratio by pre-polarizing the lamp output and including polarization recovery schemes that convert about 80% of the lamp output to a uniform polarized state. Manufacturers have also developed more sophisticated color management schemes. One method uses a holographic element to circulate the red, green, and blue light through dedicated pixels of a single device, eliminating the need to merge images from three microdisplays.

FSC systems, which use a single microdisplay synchronized to the color-wheel modulation of the arc lamp, sacrifice more

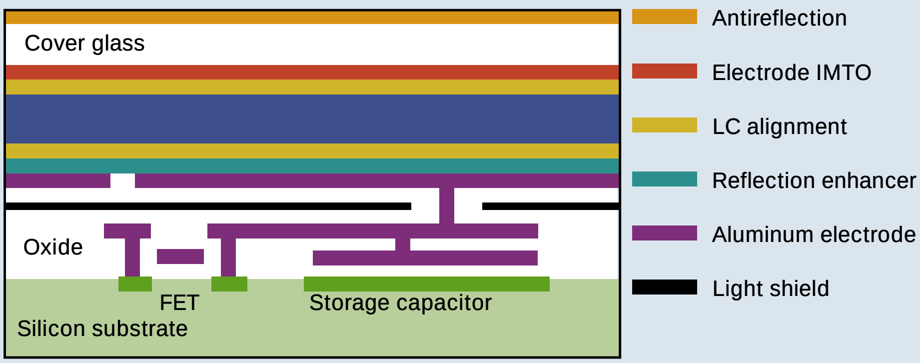
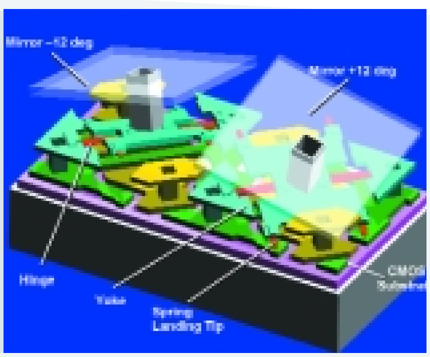


Figure 2 In an LCoS display with an index-matched indium-tin-oxide transparent electrode and field-effect transistor, the liquid crystal acts as a spatial light modulator for illumination passing through the cover glass and reflecting off the bottom layer.

than 66% of the lamp light. The efficiency is greatly improved by color-scrolling (CS) methods, which split the arc light into red, green, and blue color bands sweeping over the microdisplay area. LCoS, however, is handicapped by inefficiency at the FSC rate of more than 300 Hz that is required to avoid color breakup. The bit-plane addressing speed of the DMD accommodates 24-bit FSC and can take advantage of

Figure 3
Depending on the position of each mirror (pixel) in a DMD array, each pixel can reflect light through an aperture or away from it providing a binary on/off state.



the greater throughput of CS. In general, both FSC and CS techniques for achieving color displays lower the cost of the display but sacrifice throughput efficiency or color saturation aspects of image quality.

microdisplays

For consumer applications, the manufacturing costs of microdisplays and systems, as well as performance, will determine future developments. DMD and LCoS projectors have both achieved cinema-quality performance. Cost favors small-area microdisplays. The collimation challenges to the system imposed by small displays are met by short-arc (less than 1 mm) high-pressure lamps. Lamps producing modest power yield the extended lifetimes required for consumer products, but to satisfy image brightness demands, they must have high-throughput efficiency.

Microviewers use compact magnification systems to provide a virtual image of the microdisplays. OLED microdisplays in either monochrome or RGB pixelated format have the advantage of Lambertian emission without the illumination source requirements of nonemissive devices, which simplifies the design of the magnification optics. The optical system must include an area to interface with the viewer's eyes (an eye box) that provides an output pupil of more than 7 mm and a relief distance of about 25 mm, in case the viewer wears spectacles. Designs incorporating aspheric optics can magnify the image by about 20X; higher values require folded compound magnification schemes.

Designers realize RGB NTE viewers using color pixels or FSC schemes rather than multiple displays, which would add intolerable weight and bulk. NTE viewers deliver light efficiently to the eye, and LED illuminators can easily provide sufficient output and accommodate lower efficiency in the microdisplay. LCoS response speed is boosted at the expense of efficiency, while LED-pulsed FSC leaves more time for microdisplay response, enabling nematic LCoS to remain competitive in the market. Displays that use ferroelectric liquid-crystal, pulse-width-modulated gray scale and pulsed-LED readout have achieved 24-bit FSC. Micromirrors tend not to be used for microviewers because the limited field-of-view and pixel size of the DMD puts the technology at a substantial disadvantage.

As we mentioned during the discussion of projection displays, cost is always a factor. For consumer applications, the manufacturing costs of microdisplays and systems, as well as performance, will determine future developments. **oe**

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Technical details are available on a number of websites:
Liquid crystal microdisplays: www.aurora-sys.com, www.displaytech.com, www.microdisplay.com, www.spatialight.com, and www.threefive.com
Organic LED microdisplays: www.emagin.com and www.microemissive.com
DMD microdisplays: www.dlp.com