Mirrors on a chip

A new projection display utilizes reflections from hundreds of thousands of micromirrors, each mounted above its own memory cell

Many large projection displays may quite soon be controlled directly from a unique kind of semiconductor chip—one with a "roof" of seesaw micromirrors, each individually mounted above a memory cell. Displays based on these devices should outperform models based on cathode-ray tubes, and even vie with them in price. Computer monitors and high-definition television clearly stand to benefit. (This month's cover has already benefited.)

This revolutionary new optomechanical technology for digital projection displays is founded on the digital micromirror device (DMD), a spatial light modulator invented in 1987 by Larry J. Hornbeck, a Texas Instruments Inc. scientist. The DMD itself owes the torsion beam support of each mirror to still earlier work at TI on deformable mirror light valves.

In broad outline, the DMD covers each memory cell of a CMOS static RAM with a movable micromirror. Electrostatic forces based on the data in the cell tilt the mirror either +10 degrees (on) or −10 degrees (off), modulating the light incident on its surface. Light reflected from any on-mirrors passes through a projection lens and creates images on a large screen (systems with diagonals of 16 ft have been demonstrated). Light from the remaining off-mirrors is reflected away from the projection lens and trapped. The proportion of time during each video frame that a mirror remains in the on-state determines shades of gray—from black for zero on-time to white for 100 percent on-time. Color may be added in two ways, by a color wheel or by a three-DMD setup in development. The entire system into which the DMD fits is compared in Fig. 1 with projection displays based on either the liquid-crystal display (LCD), or the cathode-ray tube (CRT).

The standard-resolution version of the DMD corresponds to the National Television System Committee (NTSC) or Phase Alternation Line (PAL) standard. It is a chip about 2.3 cm^2 covered by 442 368 movable mirrors, each 16 μm on a side—so small that 4000 of them would be hidden by a human hair stretched diagonally across the device.

In operation, the data representing the image is written in highly parallel fashion, two lines at a time, into the static RAM. (In the first prototype designs, the dynamic RAM was not used because of concern that light from the bright illumination source might leak into the RAM and upset the data in the cell.) The static RAM is divided into an upper and a lower half, each edged by 48 input pads. Every input pad has 16 bits of serial data loaded into it, in step with every other 16-bit series—enough to write to the 768 pixels in each row. A picture plane of data can be read into the standard NTSC chip in about 140 μs at rates greater than 30 MHz.

IN CLOSE-UP. The micromirror construction and the underlying electrodes of the DMD chip appear in the insert to Fig. 2. Directly over each memory cell are two address electrodes and two "landing pads" for the seesaw mirror. Above these electrodes is the aluminum-alloy mirror, supported by hinges attached to support posts. The micromirror has three states. It operates in a bistable mode, tilting 10 degrees about the structure's torsion beams in one or the other direction. The third state is a flat position in which the mirrors are parked when the display is turned off. The scanning electron micrograph in Fig. 2 shows mirrors in all three states.

In effect, the mirror plate and the address electrodes form capacitors. When +5 V (digital 1) is applied to one address electrode, 0 V (digital 0) to the other address electrode, and a negative bias to the mirror plate, the electrostatic charge thus created causes the mirror to tilt toward the +5-V electrode. The voltage on the address electrode just starts the mirror tilting, whereupon it continues under its own momentum until it hits the landing pad. Driving the mirrors to the landing pad produces good uniformity across the DMD.

BUILDING THE 'ROOF.' To fabricate a DMD, the standard CMOS processing steps are completed through the static RAM and the offset address electrodes. Then the silicon wafer is completely coated with a polymer layer. The thickness of this layer controls the height of the micromirrors above the silicon surface.

Vias are etched through the polymer layer to the open contact sites, on which are fabricated the support posts for the hinge and mirror assembly. Next a thin aluminum hinge layer and a thicker aluminum mirror layer are deposited, patterned, and etched.

A plasma etch removes the entire polymer layer, leaving the mirrors suspended above the silicon substrate by the hinges attached to the support post. When the structure tilts, the thicker mirrors remain flat and the thinner hinges twist in torsion. The height of this superstructure over the silicon substrate is enough to allow the mirrors to tilt plus and minus 10 degrees about their torsion axis.

In effect, the mirrors have a built-in mechanical memory. Once they tilt in either direction, they stay electromechanically latched in that state by the mirror bias until a reset signal is applied, regardless of the data in the underlying memory cells. This mechanical memory is a handy means of setting all the mirrors simultaneously to the desired state for a given picture plane and then immediately loading new data for the next picture plane into the array. Put another way, the mirrors are unaffected by the data in the static RAM except for the brief time needed to restore them to the flat state and then tilt them to their new positions. Two advantages are gained: the time available for loading the data into the array

Defining terms

HDTV: high-definition TV; the standards are still being defined, but it is widely expected to have a 16:9 aspect ratio, with vertical resolution of 960 lines in the United States, 1152 lines in Europe.

Lenticular screen: a rear-projection display screen with lens-like microstructures and black vertical lines that control the refraction of light at the screen surface to provide enhanced brightness and contrast at expected observer locations.

NTSC: National Television System Committee; the commercial 525-line color TV standard adopted in 1953 for the United States; also used in North and South America and Japan. It has 483 active lines per interlaced TV frame, is specified for 60-Hz operation, and has a 4:3 aspect ratio. The number of horizontal pixels is determined by the sampling rate.

PAL: phase-alternation line; a commercial 625-line color TV standard used in Europe. It specifies 575 active lines per interlaced TV frame, is defined for 50-Hz operation, and has a 4:3 aspect ratio. The number of horizontal pixels is determined by the sampling rate.

VGA: Video Graphics Adapter; a computer display standard with a 4:3 aspect ratio and a 640-by-480-pixel format.

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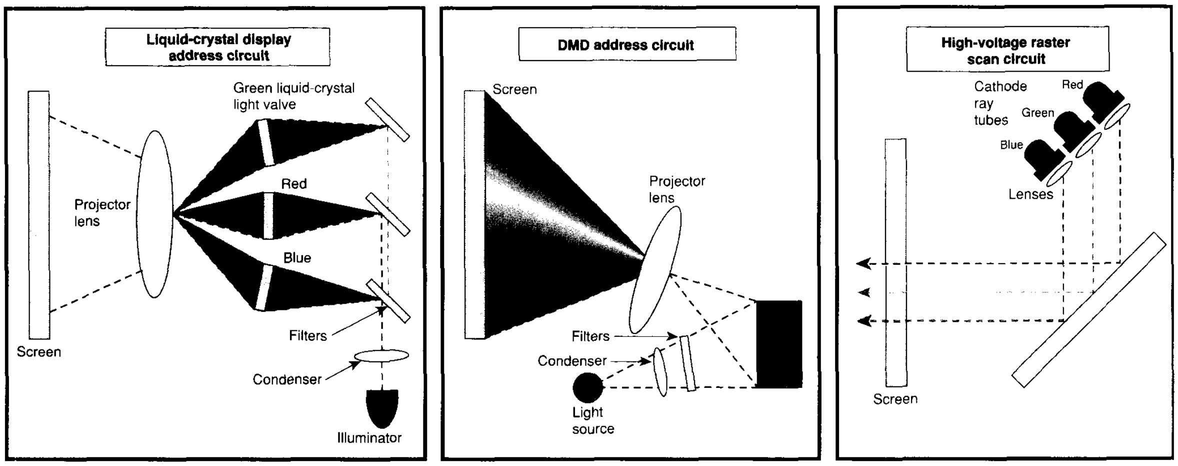
Techniques of projection display



Three-liquid-crystal light valve display

Single digital micromirror device (DMD) display

Three-cathode-ray-tube display

[1] In current projectors based on liquid-crystal displays (LCDs), dichroic beam splitters supply red, green, and blue light to trios of LCD light valves, which pass or block the light as specified by the pixel data [left]. In the display based on a single digital micromirror device (DMD), a synchronized rotating color wheel [not shown] in effect tints the light sent to the DMD chip [center]. Three consecutive 5.6-ms color fields make one 16.7-ms field, for 180 color fields per second. The cathode-ray-tube (CRT) projector contains three CRTs (red, green, and blue), each with its own cooled projection lens [right]. The images converge at a large mirror that reflects them onto a screen. Most CRT displays are rear-projection systems. Current LCD displays are mainly front-projection systems, although rear-projection systems are emerging. The DMD display is suitable for either front or rear projection, with minor modifications to the optics.

is maximized, and the speed demands on the DMD drive electronics are reduced to a workable range, below about 30 MHz.

TOWARD HIGHER RESOLUTION. An aggressive proof-of-concept program is currently under way at Texas Instruments, with support from the Advanced Research Projects Agency (ARPA), Arlington, VA, and the U.S. Air Force's Wright Laboratories in Dayton, OH. Its goal is to have a prototype high-definition display, based on DMD chips with over 2.3 million micromirrors apiece, up and running by the end of 1993. These chips will serve 2048 by 1152 pixels and be 37 by 22 mm in size, about five times the area of the NTSC chip. The device will have a 16:9 aspect ratio and use the standard 16-by-16-μm micromirror cell.

One of the biggest challenges for such a large chip is the lithography required to fabricate it. Only a few steppers available today can use standard 5× photomasks to write over such a large field and still achieve the resolution required. Some 1× steppers might be able to handle the task, but these put a heavy burden on the quality of the reticle. Currently, the high-definition chip is being fabricated with a reticle composition technique, where patterns are written in sections and spliced together to provide a virtually seamless large-area DMD chip.

IN ACTION. The digital micromirror device is most effective when coupled with dark-field projection optics [Fig. 3]. Here, a bright light source is directed to the chip at an angle to its surface of approximately 70 degrees—or 20 degrees relative to an axis perpendicular to the chip surface. Mirrors tilted +10 degrees (on) will then reflect the incoming light by a −20-degree angle through a projection lens and onto a screen. Mirrors tilted −10 degrees (off) will reflect the path of the incident light by −60 degrees so as to miss the projection lens aperture and strike a black light absorber. Likewise, flat surfaces such as hinges and support-post tops will bend the incident light by −40 degrees, so that it also misses the projection lens and is trapped.

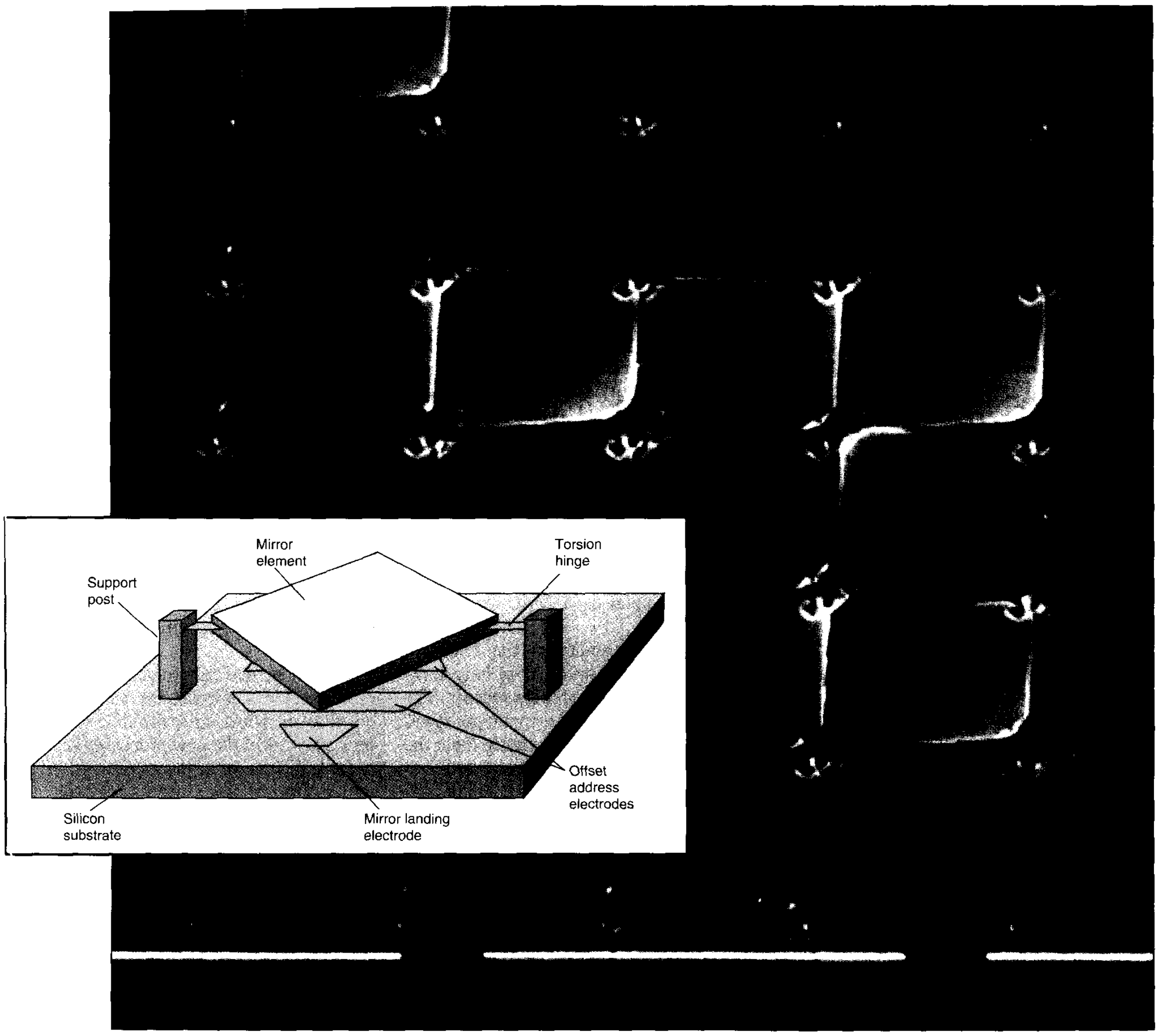
The projection system is depicted in Fig. 4. Additional optical components include two lenses. The condensing lens focuses the incoming light down to the size of the DMD chip so that all the light is used. A zoom projection lens is added to support various screen sizes.

A color projection system based on a single micromirror device also needs a rotating color filter wheel, inserted at the narrowest point along the light path and synchronized to the system electronics. The

Projection systems using digital micromirror devices (DMDs)

Projector characteristics	Single-DMD projector, NTSC-standard display	Projected values for ARPA 3-DMD projector, HDTV display
No. of DMD pixels	768 × 576	2048 × 1152 × (3 DMDs)
No. of active pixels used in demo system	640 × 480	1707 × 960
Pixel size	16 × 16 μm	16 x 16 μm
Pixel spacing (pitch)	17 μm, center to center	17 μm, center to center
Pixel aperture (fill factor)	74%	>75%
Pixel response time	10 μs	10 μs
DMD's optical efficiency	>60%	>60%
Projection type	Front	Front
Screen size	≥52 inches	≥60 inches
Picture aspect ratio	4:3	16:9
Color frame rate	180 Hz	60 Hz
Screen brightness	220 lumens	>2000 lumens
Light source	1000 W, xenon arc	575 W, metal halide
Contrast ratio	>60:1	>100:1
Gray-scale capability, per color	8 bits (256 shades)	8 or 9 bits
Color generation method	Rotating color wheel	Color prism
Pixel convergence	Self-aligned	Optical

NTSC = National Television System Committee; ARPA = Advanced Research Projects Agency.



[2] A scanning electron micrograph of a portion of the digital micromirror device (DMD) shows micromirrors in all three positions: flat, on, and off [see column of mirrors on the left of the image]. Each mirror element is 16 μm on a side. In the aluminum-alloy micromirror superstructure [inset], the mirror is suspended above the surface of the chip by support posts and the torsion hinges. It tilts into the on- or off-state when 5 V is applied to one of the two offset address electrodes (the other is grounded). The tilting motion is held at plus or minus 10 degrees by electrostatic forces. Invisible beneath the electrodes is the static RAM cell.

filter lets light of the primary colors—red, blue, and green—fall in succession on the surface of the DMD, each for a total duration of a third of the TV field (approximately 5.6 ms).

Shades of gray or color are accomplished by clocking the mirrors with a type of pulse-width modulation, so that they remain in the on-state during each TV frame for a time that is proportional to the level of gray or color desired. The conventional 8-bit system supplies 256 quantized levels for each color; that makes it possible to display more than 16 million (256^3) colors from the three 8-bit primary colors. For example, if the pixel were set at level 128, the mirror would remain in the on-state for one half the time. The human eye, being part of the overall optical system, integrates the light during each frame so that the correct hues or shades of gray are seen.

A high-definition display system based on three micromirror devices is currently under development at TI. The project has strong support from ARPA, which has long acted on its interest in high-definition display systems by investing in promising display technologies throughout the United States. A TI subcontractor in this program is the David Sarnoff Research Center in Princeton, NJ; its responsibility is the optical subassembly and the front-end electronics needed for the high-definition video source to the prototype projector.

This system will use three 2048-by-1152-pixel DMDs and will be one of the world's first truly digital high-definition displays. If successful, the program will have demonstrated long technical life for DMD displays as a system that supports both the current requirements in HDTV and those that will evolve over the next two decades. Measured performance characteristics for the single-DMD projector and expected performance characteristics for the three-DMD system are shown in the table.

The DMD is a progressive scan device, addressing every line of the display during each TV field, which means every 1/60 of a second for NTSC displays. This is both an advantage for the future and a minor drawback for the present.

Conventional CRTs operate in the interlace mode, in which every other line is written during one 1/60-second field and the alternate lines are written during the subsequent field. The glow of the phosphor in the CRT persists long enough for this technique to work. But the DMD, having no persistence, must write the entire picture every 1/60 of a second and receive data at twice the rate of the CRT. The faster electronics this necessitates makes the DMD well suited for future progressive displays. But some adjustment must be made if it is to display the video available today.

A number of methods can be employed. Two simple techniques are line doubling, which displays each line twice, and field jamming, in which the current field is superimposed over the previous field. But, depending on the content of the scene, these approaches can cause picture artifacts. A smarter idea is to use motion-adaptive algorithms implemented in hardware and software. This technique converts interlaced video into progressive scan and has been shown to be quite effective. Such an approach is currently being developed for the DMD.

STAR PERFORMANCE. Resolution, brightness, contrast, gray scale, color fidelity, and pixel response time (speed)—on all counts the DMD scores, if as yet mainly in the prototype. High resolution is inherent since the basic pixel cells are spaced on 17-μm centers both horizontally and vertically. Existing photolithographic techniques suffice, since they allow chips with hundreds of thousands or even millions of pixels to be fabricated.

The brightness of the device is due to the high reflectivity of the micromirrors (more than 90 percent for visible light) and the fact that they cover at least 75 percent of the chip surface. The remaining space consists of approximately 1-μm gaps between the mirrors, posts, and hinges. Overall, taking into account mirror reflectivity, active surface area, and such other diffractive effects as the light scattered from the mirror edges, hinges, and support-post corners, the device's optical efficiency is better than 60 percent.

When the micromirror and liquid-crystal type of projectors are compared for brightness, it pretty much boils down to the optical efficiency of the two spatial light modulators, since both projectors would be expected to use comparable light sources and optics. LCD technology is making large strides in this area, but at present, DMDs are two to three times more efficient. It is estimated that the three-DMD high-definition display currently under development could attain over 2000 screen lumens, assuming a unity-gain, front-projection screen with a 60-inch diagonal.

Contrast ratio also matters a lot in a projection display. A single-DMD projector demonstrated earlier this year has exhibited a contrast ratio exceeding 50:1, and recent results in the laboratory have shown contrast ratios more than twice as good. The DMD, being a fully digital device, measures its gray-scale capability in bits; typically 8 to 10 bits are obtainable. This translates into 256 to 1024 levels of gray for a monochrome display or for each primary (red, blue, and green) color for the more popular color projector. For example, an 8-bit color projector can generate 16 777 216 colors from 256 shades of the three primary colors. As a result, excellent color fidelity is realized by a DMD projector.

An advantage of the single-DMD projector is that the pixels are self-aligning, since each pixel reflects all the primary colors in turn. However, if the observer moves his or her head quickly relative to the screen, the color may appear to break up because of the use of a color wheel. This artifact seems not to be a serious problem for normal viewing of the display and with proper clocking of the DMD can be removed.

Although single-DMD projection systems suit low-cost consumer applications, the three-DMD variety should perform much better. For one thing, these systems are much brighter. Some two-thirds of the available light is lost in a single-device, sequential-field color system because the light is filtered to give red light for a third of the TV field, green light for another third, and blue light for the last third. In the three-device system, constant red, green, and blue light is available at each DMD for most of the TV field.

RELIABILITY. The ability of the DMD to withstand the wear and tear of long-term everyday use is essential to its success. The chips will be mounted in hermetic packages, and indications are that they should meet the temperature and environmental requirements for commercial or rugged military applications. A lot of testing must still be done in this area, but the results so far are encouraging.

One of the biggest worries many have had is the durability of the mechanical hinges. So far, many DMD chips have been tested, with every hinge exercised for several hundred billion cycles, the equivalent of about four years of continuous operation for a TV. None has shown problems with hinges breaking due to fatigue.

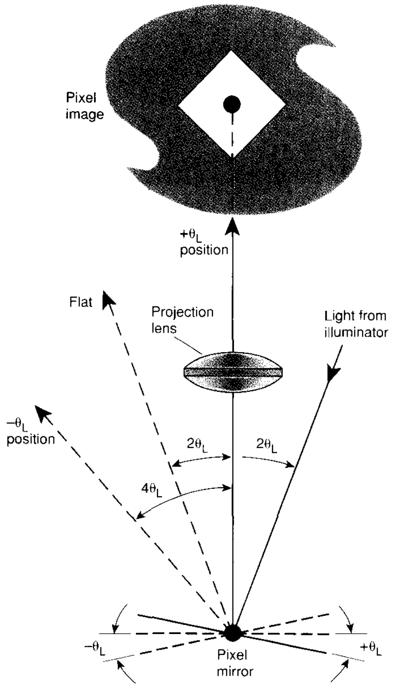
THE BOTTOM LINE. DMD technology promises to have a number of cost advantages. First, the micromirrors are fast: they can switch from being fully on to being fully off in about 10 μs. So a projection display can be based on a single DMD in field-sequential color operation. As a result, a TV field of data can be read in and displayed in one-third the time of a CRT projection display, as well as most LCD projection displays available today. So the single-DMD projector, with its simple optical components and the self-aligned convergence of the pixels, will make an attractive and relatively inexpensive display possible.

Secondly, the fabrication of the micromirror devices relies on standard semiconductor tools and mostly standard processes: even the new processes required to form the mirror layers can be carried out on existing equipment. As a result, the decline in production cost with the rise in volume can be predicted with a fair degree of confidence.

In fact, the CMOS memory underlying the micromirror structure can be manufactured on the same production lines as conventional memory chips. And although the micromirror structure is unique, the DMD was deliberately designed to use only well-known semiconductor processes. Here the advantage is that the DMDs can be manufactured side by side with other semiconductor chips, helping to fill existing factory capacities and thereby reducing capital expenditures. They are also highly compatible with other highly specialized application-specific ICs, which can be used to provide fully digital solutions for the high-volume consumer market.

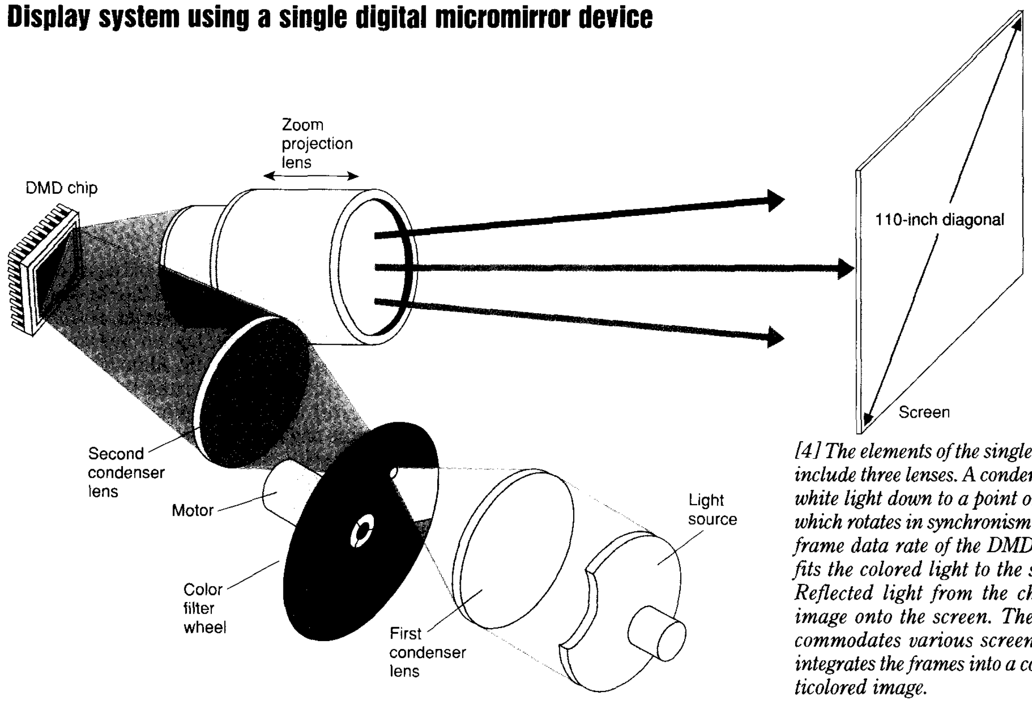
COMING SOON. Today, large-screen direct-view displays are mostly of the CRT type. But for screen sizes beyond about 38 inches on the diagonal, the glass envelopes become very heavy, bulky, and hard to handle. Therefore, for very large displays, digital projection technology looks and will probably continue to look attractive through the remainder of this century.

Whether they have the 4:3 aspect ratio of NTSC or the 16:9 aspect ratio of wide NTSC or HDTV, projection displays are primarily of two types. The 6- to 9-inch projection CRTs familiar from consumer products dominate, but then there



[3] Micromirror elements at an angle of $+\theta_L$ *to the chip surface (the on-mirrors) reflect the light from the illuminator through the projection lens and onto the screen. The off-mirrors (at* $-\theta_L$*) and flat surfaces like the support posts reflect light away from the projection lens and toward a black light-absorbing material.*

Display system using a single digital micromirror device



[4] The elements of the single-DMD projector include three lenses. A condenser lens focuses white light down to a point on a color wheel, which rotates in synchronism with the picture frame data rate of the DMD. A second lens fits the colored light to the size of the chip. Reflected light from the chip projects an image onto the screen. The zoom lens accommodates various screen sizes. The eye integrates the frames into a continuous, multicolored image.

are the spatial light modulators: DMDs are in the wings and LCDs are actually beginning to appear commercially [Fig. 1, again]. (For more on display technology see "The flat panel's future," by Kenneth I. Werner, p. 18, this issue.)

Projection CRTs, however, appear limited by the insufficient brightness of their phosphors, a deficiency that LCDs and DMDs can remedy. Moreover, DMD technology has to date been used in standard NTSC projectors and in others with Video Graphics Adapter (VGA) resolution. It is currently being ported to HDTV resolutions. By the year 2000, HDTV will in all likelihood be playing a significant role in combined entertainment, computing, and communications systems intended for home and business environments. Displays will feature wall-size projection screens having 1000 lines or more—over twice the resolution of today's TVs.

But before projection HDTV can be completely realized, some nontrivial engineering obstacles must be addressed. Future spatial light modulators will need to have higher resolution—up to 2 million pixels—and wider 16:9 aspect ratios. Chip sets capable of supporting input data rates greater than 30 MHz will require higher bandwidths. Contrast ratios of better than 100:1 are also desirable in these large-screen projectors.

New and higher-resolution screens will also be needed, especially for rear-projection applications. Front-projection screens exist today for displaying these high-definition pictures. However, high-resolution varieties of the lenticular-type screens used in rear-projectors must still be developed.

In conclusion, because CRTs are already being built in large volumes, they are well down the cost learning curve. So if spatial light modulators can enter the market at cost parity, as seems possible, there should be an advantage as volume drives their cost down. Of course, CRT projection technology will keep on improving and keep the pressure on as a viable competitor to light modulators in the marketplace.

TO PROBE FURTHER. An overview paper on the deformable mirror (now called the digital micromirror) spatial light modulator by Larry Hornbeck can be found in *Proceedings of SPIE*, Vol. 1150, Aug. 6, 1989. Two recent papers are "The digital micromirror device and its application to projection displays," by Jeff Sampsell in Society for Information Display (SID), May 18, 1993, and "The digital micromirror device and its transition to HDTV," by Jack Younse and Dave Monk in *EuroDisplay 1993*, Le Club Visu and SID, Strasbourg, France, Sept. 1, 1993. James Florence discusses DMD technology in "Optical characteristics of the deformable mirror spatial light modulator," in *Technical Digest on Spatial Light Modulators and Applications*, Optical Society of America, 1990, Vol. 14, pp. 166–169.

Three papers on the use of DMD technology in applications other than displays are: "Micromechanical spatial light modulator for electrophotography printers," by Ed Nelson and Larry Hornbeck, in *Proceedings of SPSE, Fourth International Congress on Advances in Non-Impact Printing Technologies*, 1988, p. 427; "Coherent optical correlation using a deformable mirror device spatial light modulator in the Fourier plane," by James Florence and Richard Gale, *Applied Optics*, Vol. 27, 1988, p. 2091; and "4 × 4 fiberoptic crossbar switch using the deformable mirror device," by Gus McDonald, Mark Boysel, and Jeff Sampsell, in the *Technical Digest on Spatial Light Modulators and Applications*, Optical Society of America, 1990, Vol. 14, pp. 80–83.

Pioneering work on spatial light modulators for projection displays is described in the following articles: "An array optical spatial phase modulator," by K. Preston Jr., in *Proceedings of the IEEE International Solid State Circuits Conference*, 1968, p. 100; "A new Schlieren light valve for television projection," by J.A. van Raalte, *Applied Optics*, Vol. 9, 1970, pp. 2225–30; and "The mirror-matrix tube: a novel light valve for projection displays," *IEEE Transactions on Electron Devices*, Vol. 22, 1975, pp. 765–775.

DMD inventor Larry Hornbeck will discuss recent advances in the technology in an invited paper at this year's International Electron Devices Meeting (IEDM) in Washington, DC, in December. ◆

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