The Fundamentals of Using the Digital Micromirror Device (DMD^{TM}) for Projection Display

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Lars A. Yoder
Texas Instruments Inc.
Digital Video Products
P.O. Box 655474, MS 429
Dallas, Texas 75265
214-995-2377

ABSTRACT

Developed by Texas Instruments, the Digital Micromirror Device (DMD™) is a quickly emerging and highly useful Micro-Electro-Mechanical Structures (MEMS) device (See Figure 1). Using standard semiconductor fabrication technology, the DMD's simplicity in concept and design will provide advantageous solutions for many different applications. At the rudimentary level, the DMD is a precision, semiconductor light switch.

In the initial commercial development of DMD technology, Texas Instruments has concentrated on projection display and hardcopy. The paper will focus on how the DMD is used for projection display. Other applicational areas are being explored and evaluated to find appropriate and beneficial uses for the DMD.

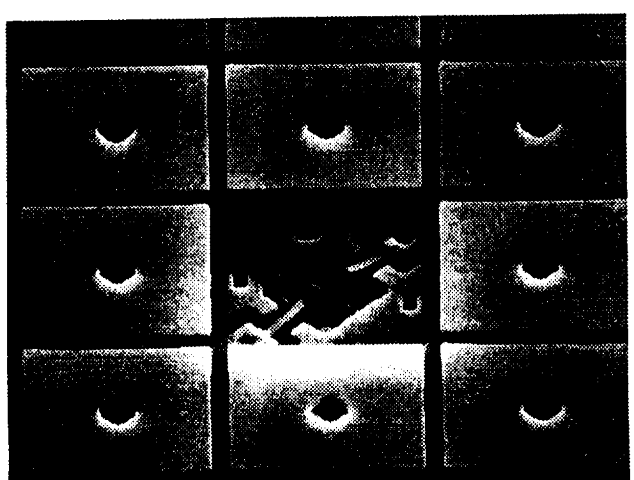

Figure 1. Photograph showing several DMD mirror elements and the mirror substructure (center).

Introduction

Starting in 1977, Texas Instruments began working on an analog light modulating technology called the Deformable Mirror Device, or DMD. This technology had limited performance and yield characteristics. By 1987, a bistable (digital) DMD was created that offered enhanced performance and showed no fundamental yield limitations. The DMD acronym was maintained but it now abbreviates the Digital Micromirror Device.

A DMD is a Micro-Electro-Mechanical Structures (MEMS) device composed of a two dimensional array of thousands of small, tilting, mirrors mounted atop of complementary metal-oxide-semiconductor (CMOS) Static RAM (S-RAM). In addition to having MEMS properties, the DMD also has an optical component, the tilting micromirrors. These mirrors, when combined with the proper optical projection system, create a truly digital process for displaying images.

Since the DMD is built over a standard CMOS circuit using conventional semiconductor processes, fabrication costs are expected to drop in line with a CMOS-like learning curve. These anticipated cost reductions have created a lot of excitement at Texas Instruments as it opens up the possibility of exploring many new markets. In investigating other applicational areas and markets for the DMD, the complete interrelationship of the DMD's MEMS and optical properties must be considered. Proper understanding of all aspects of DMD technology will give better insight as to how a DMD might become the solution to yet another technological challenge.

Markets

Texas Instruments is bringing DMD technology to the marketplace through its Digital Light Processing (DLP™) subsystem. At the core of a DLP subsystem is the DMD. Other DLP components are: memory, electronics, a power supply, a light source, a color filter system and projection optics. The goal for DLP is to compete in the projection display market; a market that is expected to have world wide sales of $4.6 billion in 1995[1].

Three projection markets have been targeted in which to sell DLP subsystems: consumer, business, and professional. The consumer market consists of front and rear-screen projection televisions. Projection television sales have been steadily increasing. This year alone, U.S. sales are up 29.1% over 1994[2]. DLP will enter the business market in the form of a conference room business projector. High brightness, 3-DMD DLP subsystems will be sold into the professional market for large screen display applications. Ultimately, these high brightness systems would be the cornerstone of future, digital cinemas.

DMD Structure

Each DMD consists of thousands of tilting, microscopic, aluminum alloy mirrors. The mirrors are 16 μm square and are separated by 1 μm gaps. These mirrors are mounted on a yoke and hidden, torsion-hinge structure which connects to support posts. The torsion hinges permit mirror rotation of +/- 10 degrees. The support posts are connected to an underlying bias/reset bus. The

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[1] Source: Stanford Resources, Inc. "Projection Displays," Second Edition, 1994-95, pg. 3

[2] Source: Television Digest, Vol. 35, No. 38, pg. 12

bias/reset bus is connected such that both the bias and reset voltage can be supplied to each mirror. The mirror, hinge structure, and support posts are all formed over an underlying CMOS address circuit and a pair of address electrodes (See Figure 2).

Applying voltage to one of the address electrodes in conjunction with a bias/reset voltage to the mirror structure, creates an electrostatic attraction between the mirror and the addressed side. The mirror tilts until it touches the landing electrode that is held at the same potential. At this point, the mirror is electro-mechanically latched in place. Placing a binary "1" in the memory cell causes the mirror to tilt +10 degrees while a "0" causes the mirror to tilt -10 degrees. Each mirror on a DMD array has the ability to modulate incident light digitally as a semiconductor light switch. Full "on" to full "off" switching time is less than 20 μs.

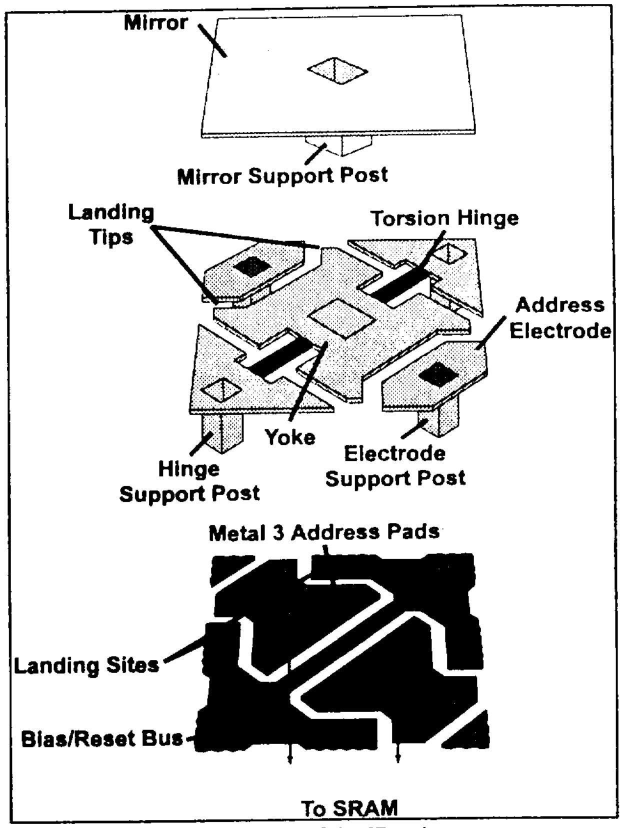

Figure 2. Exploded view of DMD mirror structure.

Mirror Assembly

The DMD chip is fabricated using 0.8 μm CMOS technology. The mirror system is built in CMOS wafer form on top of a chem-mechanical protective layer that separates the mirror system from the CMOS SRAM layer.

Construction of the mirror systems begins after contact openings for the address electrodes and bias/reset bus have been formed in the circuit's protective chem-mechanical oxide layer. Five photolithographically defined layers are surface micromachined to form the DMD mirror structure. From bottom to top, these five layers include: the metal layer that is connected to the CMOS structure via address electrodes and the bias/reset bus, a sacrificial layer, a coplanar hinge and address electrode layer, another sacrificial layer, and the reflective, aluminum alloy mirror layer. The sacrificial layers are made of an organic material that is plasma-ashed to form the two air gaps, one between the bottom metal layer and the coplanar hinge and address electrode layer, the other between the mirror and the hinge/address electrode layer. The other layers are formed from dry plasma etched, sputtered aluminum. The spacing between the mirror and bottom metal layer is 2 μm, enough room for each mirror to tilt +/- 10 degrees (See Figure 3).

After fabrication, the wafer on which the DMDs have been formed undergoes a wafer saw step. During this process, it is extremely important that the DMDs not be contaminated with particles. Micron size particles can interfere with the mechanical operation of the DMD as well as reduce its optical performance.

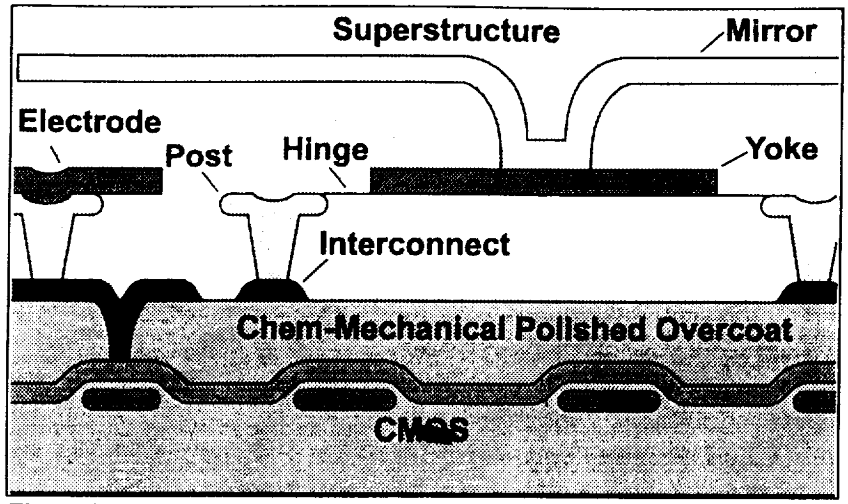

Figure 3. Cross sectional view of the DMD mirror structure.

Upon completion of the wafer saw, the chips are placed in a plasma etching chamber, where isotropic etching removes the sacrificial layers. Once these sacrificial layers are removed, the DMD finally becomes functional. Die attach, wire bond, window seal, and final test complete the sequence of assembly operations.

Video and Graphic Sources

To fully comprehend how a DMD functions in a display system, it is important to understand what needs to be displayed. The two dominant projection display sources are video and graphics. Standards for these sources are outlined below in Table 1.

NTSC: National Television System Committee-the interlaced, 60 Hz, 525 line color TV standard adopted by the United States in 1953. NTSC is also used in North and South America and Japan. Of the 525 lines, only 480 lines are active or visible to the viewer. In the interlaced mode, two 1/60 of a second TV fields make up one TV frame. Each field contains 240 alternating lines of information. As the two fields are interlaced, viewers see 480 active lines per TV frame. In the horizontal direction, NTSC TV can display about 330 vertically drawn black and white lines. This is often referred to as the horizontal lines of resolution, meaning the number of lines viewers can resolve when counting vertically drawn, black and white lines, across the picture. NTSC specifies a 4:3 aspect ratio.
PAL: Phase Alternation Line-the 625 line color TV standard used in Europe. PAL has 576 active lines per TV frame, the same 4:3 aspect ratio, operates in an interlaced mode but is specified for 50 Hz operation. PAL TV has about 420 horizontal lines of resolution.
HDTV: High Definition TV-a higher resolution TV standard that will have a 16:9 aspect ratio. Since all TV applications do not have the same requirements, multiple formats have been proposed. The highest proposed resolution is a 1,920 x 1,080 non-interlaced format.
VGA/SVGA/XGA/SXGA: Computer industry resolution standards with 4:3 aspect ratios, video, super video, extended, and super extended graphics adapter. VGA resolution specifies 640 x 480 pixels, SVGA specifies 800 x 600 pixels, XGA specifies 1,024 x 768 pixels, and SXGA specifies 1,280 x 1,024 pixels. Graphics modes are usually shown in a non-interlaced mode.

Table 1: Video and Graphics Signals standards

DMD Array Size

Depending on the requirement, DMD arrays can be configured in various formats. For projection display, arrays are built according to the resolution of the information intended to be displayed.

Initial Array

The first DMD chip was an array designed to display PAL broadcast signal, the European television standard. With square pixels, a 4:3 aspect ratio, and 576 visible lines in the vertical dimension, a DMD PAL chip is 4/3 x 576 = 768 mirrors wide. A DMD with an array of 768 x 576, containing 442,368 micromirrors was designed specifically for the purpose of displaying this PAL resolution TV signal. This chip also has the capability of displaying NTSC broadcast signal since NTSC has slightly lower resolution than PAL. When displaying the lower resolution, mirrors that are not addressed with information are simply tilted to the "off" position.

Other Arrays

Other array sizes of 864 x 576, 848 x 600, 1,280 x 1,024, and 2,048 x 1,152 have been built to support different aspect ratios and multiple resolutions of video and graphics input sources. A long, linear array of 64 x 7,056 mirrors has also been fabricated. Its intended use is to provide 600 dots per inch printing resolution across a 297 mm wide page for hardcopy applications.

HDTV Array

Demonstrating the DMD's ability to display future video sources, Texas Instruments with financial support from the Advanced Research Projects Agency (ARPA), developed a HDTV prototype projection display system. This system was designed to display the highest proposed 16:9 HDTV resolution, 1,920 x 1,080. The projector is based on three DMD chips, each containing 2.3 million, 16 μm square, micromirrors in 2,048 x 1,152 arrays. The project was successfully completed at the end of 1993, solidifying DMD display technology as a competitive solution for displaying current and future, video and graphics information.

DMD Display and Systems

Every time a binary "1" or "0" is delivered to the memory cell directly below each mirror, the proper address electrode is activated, and the mirror tilts to the "on" or "off" position. By using the DMD as a spatial light modulator, light incident on each of the thousands of mirrors on the chip can be precisely reflected to, or away from, a lens configuration. The light transmitted through the lens system is imaged onto a screen. The light that is reflected away from the lens system hits a black, light absorbing material. Through this process, a digitally projected image is possible (See Figure 4).

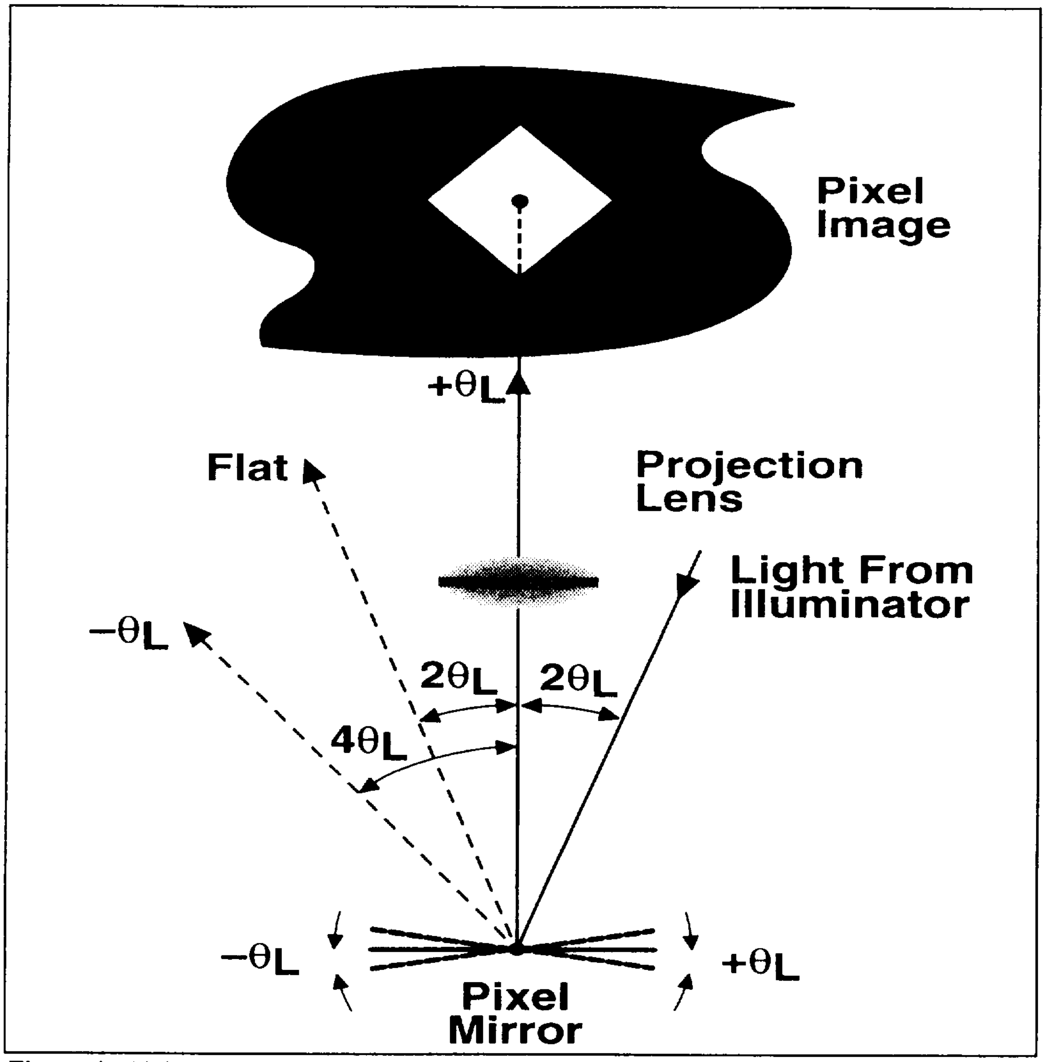

Figure 4. Light is directed onto the surface of the mirror at 20 degrees relative to the optic axis (which is perpendicular to the surface of the chip). A mirror that is tilted +10 degrees to the "On" position will direct the incident light directly up the optic axis, through a projection lens. This light then forms a pixel image on a screen. A mirror that is tilted -10 degrees will reflect light -40 degrees from the optic axis, away from the projection lens. This light is directed towards a black, light absorber.

Grayscale is achieved through a digital technique called pulse width modulation (PWM). With PWM, the amount of time that a mirror is "on" for a given TV field is controlled by the binary code sent to the memory cell. By varying the time the mirror is on, grayscale levels are generated.

For example, if 128 grayscale levels are desired, a 7 bit binary signal would be used (See Figure 5). The most significant bit is assigned to half of the TV field while. Proceeding bits are assigned to half of the remaining TV field with the least significant bit being assigned to 1/128th of the TV field. The DMD mirrors will tilt "on" or "off" for the given bit and the amount of reflected light is integrated by the human visual system to create perceived intensities or grayscale levels.

Color is added through a color filter or prism system, depending on the application and performance requirements.

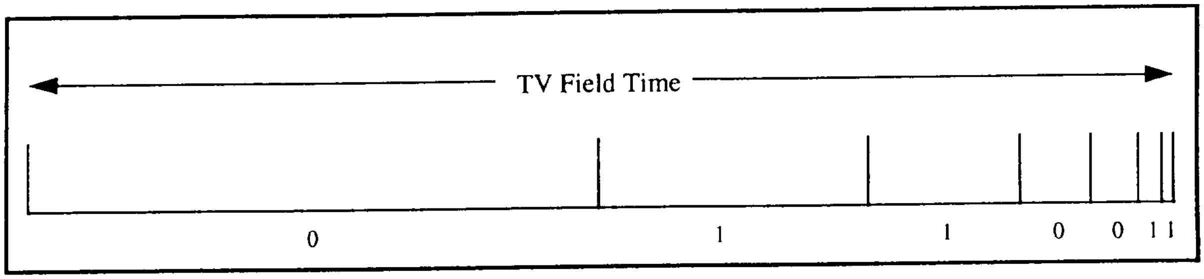

Figure 5. A 7 bit Pulse Width Modulation (PWM) code gives $2^7 = 128$ grayscale levels. The human visual system integrates the light that is reflected or "on" during the TV field and grayscale levels are realized. The 7 bit signal of 0110011 results in an intensity encoding of 40%, or a grayscale level of 51.

Video Projection Display

Currently, a video TV frame consists of two interlaced fields. One field writes every other line and the subsequent field writes the alternating lines. Interlacing works well for cathode ray tube (CRT) display because the phosphor glow persists long enough to make the image visible. DMD projection display is inherently a non-interlaced or progressive display technology; the entire array of mirrors is addressed for each TV field. It is therefore necessary to convert conventional interlaced TV signals into a non-interlaced format.

Several techniques can be adopted to convert interlaced signals into non-interlaced ones: line doubling, field jamming, and adaptive motion interpolation. Line doubling simply displays each TV line twice during the TV field, filling in the space between alternating lines. With field jamming, a memory buffer stores one of the interlaced fields and displays it with the other field, superimposing the two fields. Adaptive motion interpolation looks at the alternating lines in real-time, on a pixel-to-pixel basis, and "interpolates" what the picture should look like in between the two lines. The interpolated information is then scanned in between the alternating lines. This seems to be the best approach to compensate for motion artifacts that are more noticeable when the other two techniques are used. Proper conversion of the interlaced signal into a progressively scanned signal also has the advantage of increasing the apparent perceived resolution of the projected image.

Graphics Projection Display

The majority of computer monitors today operate in a non-interlaced mode. They scan every line and write the entire frame in just one field. Without non-interlaced scanning, the fading of the phosphors between each alternating line can be more noticeable, causing the screen to flicker.

Since the DMD shows a full, progressively scanned image, it couples well with graphics inputs and displays razor sharp graphics images. Ideally, a DMD used for graphics projection would map each pixel of information to its own mirror. This way, exact digital pixel control can be achieved. It is also possible to display higher resolution graphics sources on a DMD having less mirrors than pixels through the use of scaling techniques.

1-Chip System

In a single DMD projection system, a color wheel is used to create a full color, projected image. The color wheel is a red, green, and blue, filter system which spins at 60 Hz to give 180 color fields per second. In this configuration, the DMD operates in a color field sequential mode.

The input signal is broken down into red, green, and blue (RGB) components. The signal goes through the DMD formatter and picture buffer electronics. It is then written to the DMD's SRAM. A white light source is focused onto the color wheel through the use of condensing optics. The light that passes through the color wheel is then imaged onto the surface of the DMD. As the wheel spins, sequential red, green, and blue light hits the DMD. The color wheel and video signal are in sequence such that when red light is incident on the DMD, the mirrors tilt "on" according to where and how much red information is intended to be displayed. The same is done for the green and blue light and video signal. The human visual system integrates the red, green, and blue information and a full color image is seen. Using a projection lens, the image formed on the surface of the DMD can be projected onto a large screen (See Figure 6).

Since a NTSC TV field is 16.7 ms (1/60 of a second), each of the primary colors must be displayed in about 5.6 mili-seconds. Given that the DMD has <20 μm switching time, 8-bit grayscale per color (256 shades) is possible with a single DMD system. This gives 256 shades for each of the primary colors or, $256^3 = 16.7$ million possible colors that can be generated.

When a color wheel is used, 2/3 of the light is blocked at any given time. As white light hits the red filter, the red light is transmitted and blue and green light is absorbed. The same holds true for the blue and green filters; the blue filter transmits blue and absorbs red and green, the green filter transmits green and absorbs red and blue. The result is that a 1-chip system is inefficient in its use of light, however, for certain applications, this approach offers an excellent price/performance match.

3-Chip System

Another approach is to add color by splitting white light into the three primary colors by using a prism system. In this approach, three DMDs would be used, one for each of the primary colors. The main reason for using a 3-DMD projection system is for improved brightness. With 3 DMDs, light from each of the primary colors is directed continuously at its own DMD for the entire 16.7 mili-second TV field. The result is that more light gets to the screen, giving a brighter projected image. In addition to increased brightness, higher bit color can be realized. Since light is directed to each DMD for the whole TV field, 10 or 11-bit grayscale per color is possible. This highly efficient, 3-chip projection system would be used for large screen and high brightness applications.

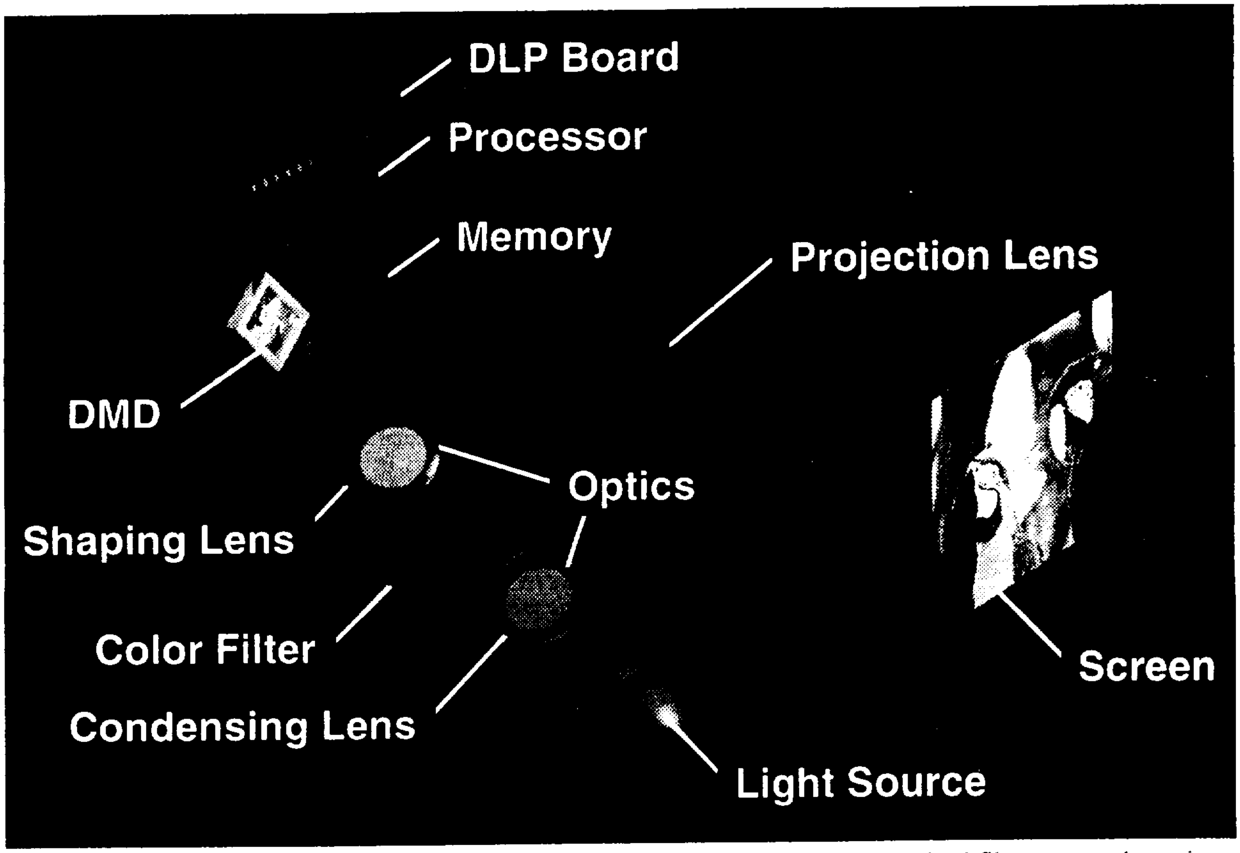

Figure 6. 1-chip, DMD projection system: White light is focused down onto a color wheel filter system that spins at 60 Hz. This wheel spins in sequence with the red, green, and blue video signal being sent to the DMD. Mirrors are turned "on" depending on where and how much of each color is needed for each TV field. The human visual system integrates the sequential color, and a full color image is seen.

Advantages

DMD based projection display systems have many advantages over the existing Cathode Ray Tube (CRT) and Liquid Crystal Display (LCD) projection technologies.

Pixel Fill Factor and Uniformity

DMD chips with 16 μm square mirrors spaced on 17 μm centers have a fill factor of up to 90%. In other words, 90% of the pixel/mirror area can actively reflect light to create a projected image. Pixel size and gap uniformity is maintained over the entire array and is independent of resolution. LCD's have at best, a 60% fill factor. CRT's are not capable of producing square pixels since they rely on an electron beam scan, not a pixelated array. The DMD's higher fill factor gives a higher perceived resolution, and this, combined with the progressive scanning, creates a projected image that is much more pleasing to the eye than conventional projection display.

Light Efficiency

The DMD is capable of having an overall light efficiency of over 60%. The definition of light efficiency here is simply the percentage of output light as compared to the amount of input light.

For a DMD, there are four multiplying components that make up its light efficiency: a temporal component, the reflectivity of surface, the fill factor, and diffraction efficiency.

DMD Light Efficiency = (Actual time "on") x (Re. of Surface) x (Fill Factor) x (D. Efficiency)

= (92%) x (88%) x (90%) x (85%) = 61.9%

LCD projection displays are inherently light inefficient. First, they are polarization dependent so one of the polarized light components, or half of the lamp light is not used. Other light is blocked by the transistors, gate, and source lines in the LCD cell. In addition to these light losses, the liquid crystal material itself absorbs a portion of the light. The result is that only a small amount of the incident light gets transmitted through the LCD panel and onto the screen.

Higher Resolution and Brightness

Increasing the input resolution simply means that more mirrors on the DMD have to be activated. Higher resolution can be achieved independent of brightness. As brightness is increased with CRT projectors, the phosphors "bloom" causing resolution to drop. In a DMD projection system, increasing brightness simply means that more light is reflected off of the DMD and onto the screen, with no loss in resolution. The amount of brightness for a given DMD system is a function of the light source used and the number of DMDs in the system. Several hundred to thousands of lumens of brightness can be displayed using DMD technology. This provides flexibility to both the manufacturers and markets that DMD projection display will serve. The DMD's higher resolution and brightness capabilities makes it more desirable for current and future projection display applications.

Digital Control

Each pixel of information displayed on a screen is precisely and digitally controlled independent of surrounding pixels. Spatial repeatability is achieved and through the use of PWM, grayscale and color levels can be accurately repeated, time after time.

Reliability

The DMD has passed all standard, semiconductor qualification tests. In addition to these tests, Texas Instruments has evaluated the DMD's performance reliability for the DLP subsytems that will be sold to the three previously mentioned markets: consumer, business, and professional. The DMD has passed a barrage of tests meant to simulate actual DMD environmental operation including: thermal shock, temperature cycling, moisture resistance, mechanical shock, vibration, and acceleration testing.

Because the DMD relies on a moving hinge structure, most of the reliability concerns are focused on the hinge life. To test hinge failure, approximately 100 different DMDs were subjected to a simulated one year operational period. Some devices have been tested for over 1 trillion cycles, equivalent to 20 years of operation. Inspection of the devices after these tests showed no broken hinges on any of the devices. Hinge failure is not a factor in DMD reliability.

Conclusion

Produced using standard semiconductor processes, the DMD is becoming a highly useful optical MEMS device for projection display. Device reliability has been validated leaving no reason to inhibit marketplace acceptance. Other applicational areas for DMD technology are being evaluated but the current thrust for DMD deployment into the marketplace is in the area of projection display. DMD and DLP technology will offer many performance advantages over current projection display technologies. High speed operation, brightness, resolution, fill factor, high optical efficiency, and 16.7 + million color reproductions are all advantages of DMD projection display. Combining these DMD advantages with complete digital control makes DLP an exciting new technology. Texas Instruments' Digital Light Processing, based on the DMD, offers an excellent solution for projection display as the world begins to enter into a true, digital, multimedia age.

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