Plano, Texas ▪ May 1, 2008

Texas Instruments

The Digital Micromirror Device

A Historic Mechanical Engineering Landmark

DLP® Texas Instruments

ASME Setting the Standard

HISTORIC MECHANICAL ENGINEERING LANDMARK

DIGITAL MICROMIRROR DEVICE

1996

THE DIGITAL MICROMIRROR DEVICE (DMD), REPRESENTED HERE BY ONE OF THE FIRST UNITS PRODUCED, IS A WIDELY USED OPTICAL MICROMACHINE FOR DISPLAY APPLICATIONS. THE DMD MANIPULATES LIGHT DIGITALLY THROUGH THE MECHANICAL ACTION OF UP TO TWO MILLION MOVABLE, INDIVIDUALLY CONTROLLABLE MICROMIRRORS FORMED ON A SILICON INTEGRATED-CIRCUIT CHIP. EACH MICROMIRROR MUST BE CAPABLE OF SEVERAL TRILLION CYCLES WITHOUT FAILURE.

A MULTI-DISCIPLINARY TEAM OF ENGINEERS AND SCIENTISTS AT TEXAS INSTRUMENTS INC. DEVELOPED THE DMD TECHNOLOGY FROM CONCEPTION IN 1987 TO ITS FIRST COMMERCIAL APPLICATION AS AN ELECTRONIC PROJECTION DISPLAY IN 1996. A WIDE RANGE OF VIDEO-DISPLAY APPLICATIONS USING THE DMD HAS FOLLOWED.

ASME THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS 2008

The Beginning of the Digital Micromirror Device

In 1977, at Texas Instruments (TI), a small team formed under the direction of Dr. Larry Hornbeck. This group would eventually develop the Digital Micromirror Device (DMD) – an optical micromachine that would power the most versatile display technologies in the world, including pocket projectors weighing less than one pound (0.5 kg) and digital cinema projectors lighting up 70-foot (21.5 m) screens. The artifact being designated as an ASME Historic Mechanical Engineering Landmark is one of the earliest usable digital micromirror devices produced.

The innovative pursuit of digital light processing technology began with the invention of the light-manipulating DMD, but success wasn't achieved instantaneously. Instead, the journey was littered with mistakes, failures and shattered concepts, all fueled by dogged perseverance and sheer determination that refused to quit on an idea destined to revolutionize the television and film industry. As Hornbeck, a noted physicist, would remember, "If you're afraid you may fail, then your actions may not be as bold, aggressive or creative as you need them to be in order to accomplish your goal. You may play it so conservative you never get there." Hornbeck and his team were determined to get there.

The DMD and the Department of Defense

In the mid 1970s, TI worked with the Department of Defense (DoD) to develop charge-coupled-device (CCD) imagers, a light sensitive integrated circuit which converts a light image into an electronic image. TI was known for its expertise with the design and manufacture of a rather unconventional CCD that was fabricated on a thinned silicon substrate and backside illuminated. Applications included low-light-level imaging, where the CCD was part of an image intensifier tube, and moving target indicators, where the CCD was manufactured with the capability of storing and comparing multiple images.

In 1977, TI's experience with thinned, backside-illuminated CCDs played a pivotal role in the DoD's decision to fund TI for a new project. But the objective of this new project was to develop a device to modulate light rather than to image with light, a crucial distinction and one that would start TI on a completely new path that would ultimately lead to the DMD. Hornbeck was chosen to head this new project because of his recent experience with developing the moving target indicator CCD.

The original approach was a hybrid structure that combined a thinned CCD with a deformable mirror, a metalized polymer membrane that would be manufactured on the backside of the CCD. Rather than detecting an image, the CCD essentially operated in reverse, providing electronic signals to electrostatically control the deformation of the mirror. Each CCD picture element (pixel) controlled one pixel of the deformable mirror. A few months into the project, the manufacturing challenge of combining a thinned CCD with a deformable mirror was fully appreciated, and Hornbeck proposed a more easily fabricated hybrid structure, using n-type metal-oxide semiconductor (nMOS) transistors to control a deformable mirror manufactured just above the transistors.

In late 1980, Hornbeck filed the initial patent for the deformable mirror device or DMD. It described in detail how an analog voltage, developed by a transistor within each pixel, could be applied across an air gap, resulting in an analog deformation of the metalized membrane into the air gap – the greater the voltage, the greater the deformation, and with a judiciously-placed optical stop, the greater the light intensity of a projected pixel image.

By 1981, Hornbeck shifted his focus from metalized membranes to a technology that, in principle, could be more easily manufactured in a standard semiconductor fabrication facility; a monolithic structure consisting of all-metal, reflective cantilever micromirrors integrated along with a nMOS address circuit on a silicon substrate.

About the same time, Dr. Ed Nelson, an expert in optical imaging, joined Hornbeck and expressed his conviction that the technology was well-suited as a "light bar," a line array of pixels that could replace the laser scanner commonly employed in electrophotographic printers. Over the next several years as Nelson worked the printer application, Hornbeck developed improved DMD architectures and manufacturing methods. TI's Chief Technology Officer, Dr. George Heilmeier provided some funding to keep the team moving forward, and perhaps, more importantly, he provided encouragement to Hornbeck and Nelson.

From Printers to Projectors to Televisions

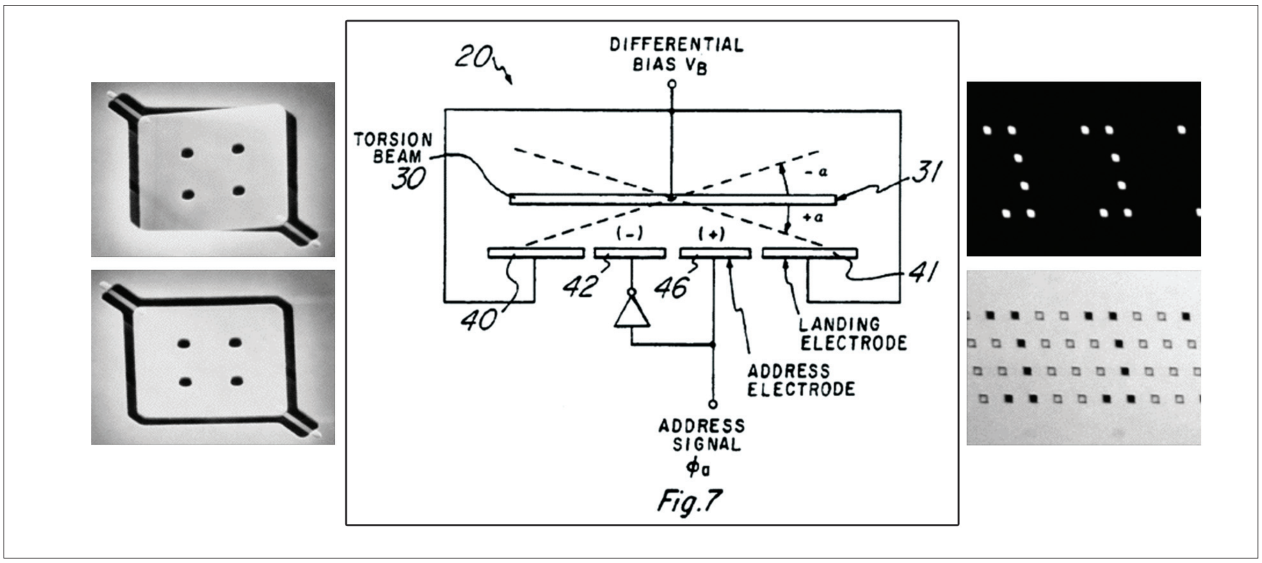
By mid-1986, it was apparent that the analog cantilever-mirror DMD would not be successful in meeting the requirements for printing or display applications. So early the following year, Hornbeck devised a radically new approach to modulating light with micromirrors. He began using the micromirrors as simple on-off switches to create pulses of "digital light." The potential advantages included improved optical performance and operation at lower voltages that were compatible with standard complementary metal-oxide semiconductor (CMOS) transistors. For display applications, he implemented pulse-width modulation (PWM) techniques to simulate analog grayscale. Thus, the basis for what would become the "digital" DMD was underway.

In 1987, TI built and tested the first "digital" DMD, a 512-pixel line array of addressable micromirrors. Each micromirror was suspended by a pair of torsion hinges (or flexures) above a pair of address electrodes placed on the surface of the silicon chip. The direction of mirror rotation was selected according to which address electrode of the pair was energized. Mechanical stops limited rotation to ±10 degrees. Combining the DMD with a light source and optics, the projected optical image of each mirror could be rapidly switched on (+10 degrees) or off (-10 degrees).

Although the new digital technology had much to offer, it was a radical departure from the technology and product roadmaps of printer manufacturers. By late 1991, TI delivered an 840-pixel DMD line array to its own printer division for application in the first commercial DMD product, a high-speed airline ticket printer which shipped to customers starting in 1992.

Hornbeck filed a patent application on March 16, 1988 for the new digital architecture, receiving U.S. Patent Number 5,061,049, "Spatial Light Modulator and Method" on October 29, 1991. This patent formed the basis for the current digital DMD, renamed the digital micromirror device in 1992.

But the road remained rocky for the DMD. Some couldn't see a future for the technology and getting space in the semiconductor development wafer fabrication facility to build the devices was a continuing struggle.



The first "digital" DMD developed in 1987.

- *(Left) Tipped and flat micromirrors. Each pixel consisted of a micromirror connected to stationary anchors by a pair of torsion hinges.*
- *(Center) Concept drawing reproduced directly from U.S. Patent 5,061,049 illustrating how a digital micromirror is electrostatically switched.*
- *(Right) A small portion of a 512-pixel digital DMD with a pattern of tipped and flat mirrors shown under darkfield and brightfield illumination conditions.*

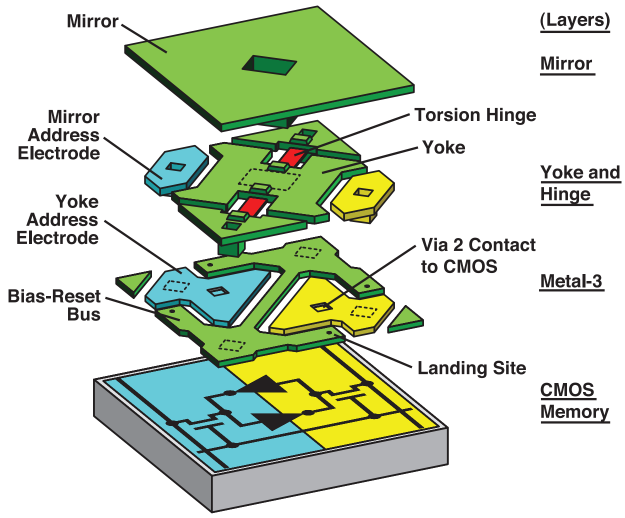
In 1988, Jeff Sampsell, manager of TI's optical processing branch, learned of an upcoming defense research program to explore the concept of high-definition television (HDTV). Sampsell was convinced that DMD was the answer, even if the application would require placing 2 million micromirrors on the face of a silicon chip not much larger than a postage stamp. After initial rejection of his proposal, the DoD awarded TI an HDTV development contract in early 1989.

Later that same year, the Rank Corporation, a major player in the motion picture and entertainment industry, provided funds for TI to develop high brightness, large-screen projectors based on a concept using beam-splitting prisms and three DMD devices. The combined investments probably made the difference between success and failure for DMD technology. Hornbeck realized the momentum toward HDTV applications for his DMD and quickly filed two key patent applications in 1989 that focused on transforming the DMD from a printer technology to a display technology.

The first patent application replaced the staggered rows of pixels and the exposed hinges of the "light bar" printer configuration with an array of close-packed micromirrors having torsional flexures "hidden" under the mirror so as not to scatter light from the projection lamp. The result was greater light efficiency, a "seamless" image, and greatly improved contrast ratio.

The second patent application provided for a DMD addressing method suitable for rendering high-quality grayscale images using pulse-width modulation. In the PWM method, the video frame period is divided into many small discrete time periods called bit segments during which any given mirror is either "on" or "off" depending on whether its memory cell was previously addressed to a "1" or "0". Using the principle of electromechanical latching, this patent application described an efficient means of loading electronic bits to the memory cells while simultaneously displaying optical bits.

In 1991, TI formed a corporate-level venture project and built a dedicated wafer fabrication facility to focus on digital video display applications for DMD. At that time, cathode ray tube (CRT) technology was typically used for most video images, while liquid crystal display (LCD) technology was the default winner in the infantile projection display business.

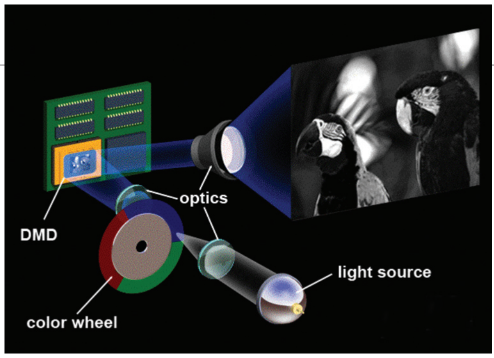


An exploded view of a "hidden hinge" DMD pixel (1995).

When the team began to concentrate on the digital signal processing aspects of the DMD projector concept, they realized that the strength of what came to be called "digital light processing" was its ability to use a high-speed stream of optical bit segments to create a faithful rendering of analog grayscale images.

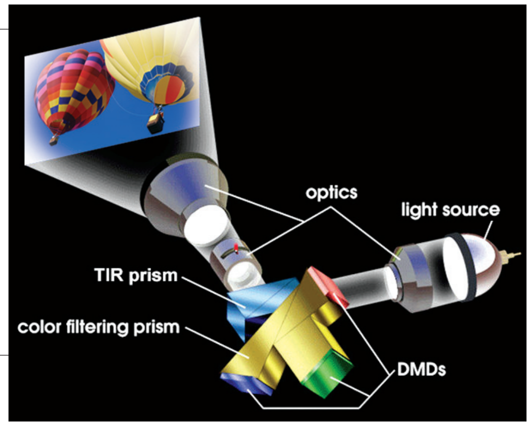
Projectors based on digital light processing provided advantages over their analog counterparts including picture reliability (stable image quality over time), functional reliability (long lifetime), and versatility. The short switching time of the micromirrors and their high optical efficiency allowed for both one- and three-chip digital light processing projector systems.

So out of DMD technology, DLP® systems were born. The DLP system, which incorporates a light source, one or three DMDs, color-splitting prisms or color wheel, digital formatter and processor chip with embedded algorithms, and projection optics, provided very stable images and enabled compact DLP projectors using a single DMD chip, as well as very bright DLP projectors using three DMD chips.



<< [A diagram illustrating how a one-DMD projection system works.

A diagram illustrating how a three-DMD projection system works.] >>



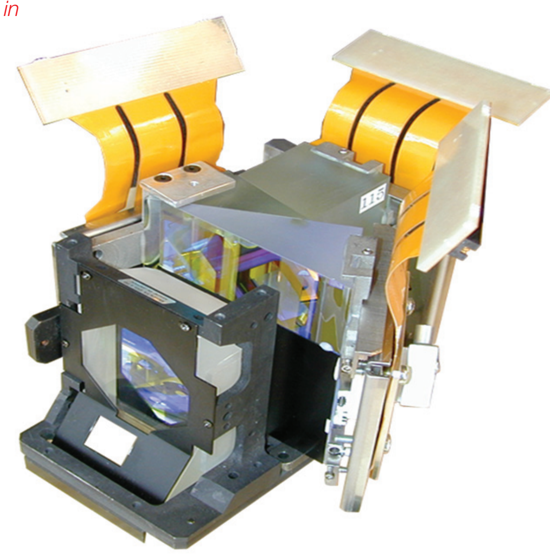
<< [

First hidden hinge DMD (1993). The array size is 768 x 576, and the portion projecting an image is 640 x 480. This unique photo captures a historical event, an integrated circuit producing a projected image the size of a man. The field of view of the projection lens was increased to show not only the DMD chip, but also the surrounding package and the bond wires that electrically connected the chip to the package contacts. For size reference, the image diagonal at the DMD chip is 0.53 inches, and the bond wires are one-thousandth of an inch (25 microns) in diameter.

Digital Projection

By 1996, the team saw a natural fit for its DLP technology – the digital projection market for conference room use. By April of that year, the first one-chip DLP subsystems were delivered to manufacturers. By December, they were working with InFocus Systems, the world's No. 1 projector company, to develop a projector that was twice as bright and weighed less than seven pounds (3 kg) – less than half the weight of projectors in the market.

<< [The first DLP "light engine" delivered to manufacturers in April 1996.



The optical elements of a three-DMD projector (shown without the projection lens). The central structure is a color-splitting and recombining prism assembly. It is surrounded by three DMDs, one dedicated to each primary color (red, green and blue).] >>

When the product was introduced a year later, it revolutionized the conference room projection market. DLP technology quickly captured a 20 percent share of the market, and DMD array sizes were increased from 500,000 to more than 1 million micromirrors. In time, DLP projectors would weigh less than two pounds (1 kg).

Although DMD fabrication used standard TI material, equipment and processes, it proved to be a significant challenge when considering all aspects of the technology including electrical, optical and mechanical performance. These challenges were met by a multi-disciplinary team of engineers and scientists, resulting in growth from a small laboratory environment producing thousands of units per quarter to a worldwide mass-production environment of multiple factories producing more than 1 million units per quarter.

Once DLP technology was proven to be viable in the front-projection space, it was implemented in the rear-projection TV market. In 1998, with the promise of HDTV on the horizon and the increased consumer preference for large screen sizes, several Japanese companies decided to develop DLP televisions. The new sets received critical acclaim at home and abroad.

Digital Cinema

During the late 1990s, the DMD found a place in digital cinema – bringing large screen image quality that would rival and ultimately replace film in the motion picture industry. The benefits of digital media were simple to understand. There would be the easy, non-physical distribution of the video content and non-degradable image quality without fading colors or scratches. The digital projection's future would mean no more reels to change or complicated machinery to operate. Mainstream digital projectors would be as simple to operate as pushing a button or pointing and clicking on a computer screen.

The industry, however, wasn't convinced. Movie studios feared that pirating could represent a serious loss of revenue because, unlike a VCR, the digital medium did not degrade when multiple copies were made of a motion picture. And theater owners did not relish the thought of increased financial investment in new projectors. To address the industry's concerns, in 1997, TI's DLP Cinema® team began meeting with the Hollywood creative community – producers, directors and cinematographers, along with those individuals responsible for editing and duplicating movies. They took notes from distributors, movie theater owners, agents, actors, audiences and even ushers about what made a great motion picture, and the team began incorporating the ideas they heard into a new prototype for the projector. These improvements were incorporated into other DLP products as well.

A DLP Cinema® projector similar to the one shown here was used at the first digital cinema premiere.] >>

George Lucas opened the door for digital cinema in 1998 when he announced he would release "Star Wars: Episode I – The Phantom Menace" in digital format and exhibit it with digital projection. The results were spectacular when shown using two DLP Cinema projectors in New York and Los Angeles.

As "Menace" producer Rick McCallum said at a press conference on June 17, 1999, the day before the digital premiere, "For filmmakers, this brings the in-theater experience a lot closer to what could be seen on set during shooting, which is what the director wants the audiences to see. This is a turning point in film exhibition."

Future Applications

The DMD has been attractive for many non-imaging applications because of its optical broadband capability from near ultraviolet (400 nm) to near infrared (2500 nm) wavelengths and its high data bandwidth. Beyond projectors, HDTV and cinema, some applications benefiting from this innovation include the volumetric display and the programmable spectral processor.

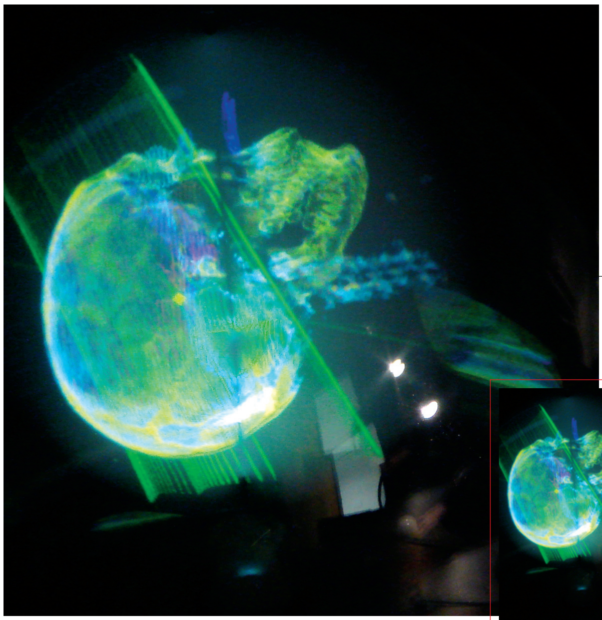
In volumetric displays, DLP projectors with three DMDs are used to render 3-D images that appear to float in space without the use of stereo glasses or headsets. In one example of a volumetric display, the 3-D rendering involves projecting a time-sequential set of 2-D views of the 3-D image onto a rotating surface. The high-speed capability of DMD enables as many as 5,000 projected 2-D views per second.

Applications for volumetric displays include real-time visualization of 3-D graphics from medical imaging, drug discovery, oil and gas exploration, and homeland security. For example, before treating a tumor, a volumetric display may enable more accurate planning of how to direct the radiation beams so as to minimize damage to surrounding tissues without compromising efficacy.

In the programmable spectral processor, DLP technology allows input broadband radiation to be customized in real time to just about any output spectral profile. Its applications include subnanometer spectral shaping, fiber sensing, spectral gain flattening, optical coherence tomography, optical filter testing and advanced telecommunications development.

In only a few years, this little machine has had a big impact on the information and communication world. Like some other fundamental devices, DLP chips hide in the background. They are seldom seen by those who use them without a thought about how these tiny machines reliably perform trillions of operations. For example, while watching a movie projected by DLP Cinema technology, no audience member would suspect that hidden away inside the projector are more than 6 million digital micromirrors, each flipping more than 30 million times during a movie of average length for a total of 180 trillion mirror flips.

While the DLP technology has already come of age in a variety of display applications including projection, HDTV and digital cinema, many other areas may benefit from this micromachine technology including metrology, remote sensing, machine vision, optical communications, 3-D volumetric displays, spectroscopy and hyperspectral imaging, holographic data storage, medical devices, security and surveillance, lithography, confocal microscopy, head-mounted displays, 3-D LADAR systems, and spectrally tunable light sources. The potential for DLP technology is limitless.



Actuality Systems Perspecta® Spatial 3D is an example of a volumetric display that uses three DMDs to create 3-D images viewed without glasses or headsets. 3-D images such as this one, ultimately lead to improved treatment planning for brain tumors since they accurately pinpoint the areas which should receive radiation.

Dr. Larry Hornbeck

Many individuals have contributed to DMD and DLP technology over the years. But the primary architect of the DMD concept and its microelectromechanical design and manufacturing process is Larry J. Hornbeck.

Hornbeck joined the Central Research Laboratories of Texas Instruments in Dallas, Texas, with a Ph.D. in solid state physics, in 1973. He began his career developing new CCD image sensor architectures, but in 1977, he turned from image sensors to developing spatial light modulators (SLMs) based on what is known today as microelectromechanical systems (MEMS) concepts. In a little more than 20 years, his radical approach to the MEMS architecture became the heart of the products enabled by DLP technology.

Hornbeck is currently a TI Fellow. He works in the Technology Development organization of DLP Products.

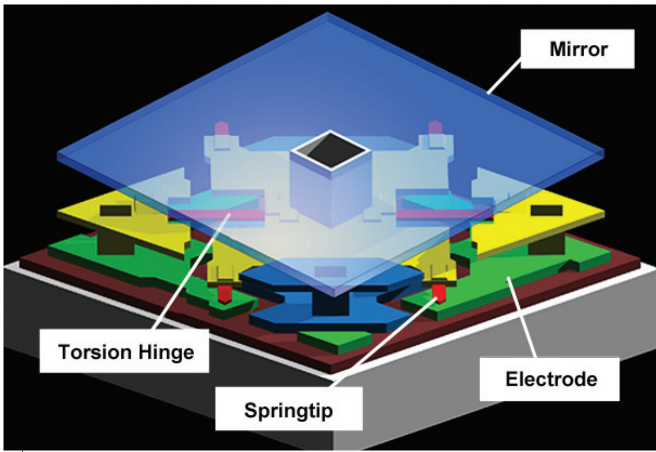
The Role of the Micromirror

TI supplies DLP component sets to display manufacturers. Each set includes a DMD, a digital video processor and formatter ASIC, and a mirror control waveform generator.

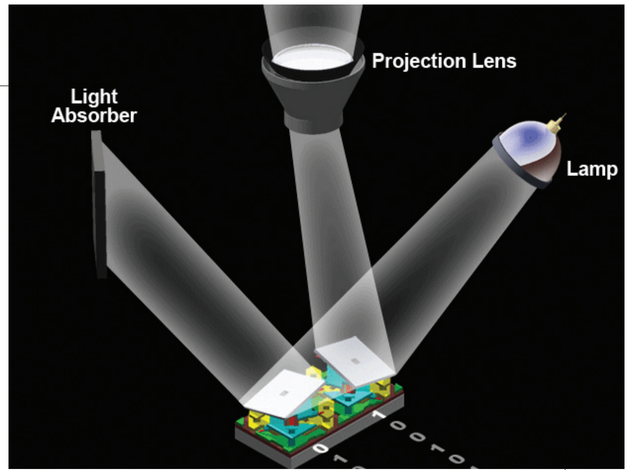
DMD chips are available in various array sizes from 640 x 480 (~0.5 million mirrors) to 2048 x 1080 (>2 million mirrors). Each micromirror represents one pixel in a projected image. The micromirrors are electrostatically actuated and are capable of "switching" very quickly between two stable rotational states (±12 degrees) according to whether a "1" or "0" is stored in an underlying memory cell. A pixel is bright when the mirror is "on" (+12 degrees) and dark when it is "off" (-12 degrees).

As part of a "digital light processing" system each micromirror functions as a very fast binary optical switch, having the capability of "chopping" light that is reflected from its surface and imaged on the projection screen, into more than 5,000 optical bit segments per second.

A DLP system combines an illuminator, color filters, one or three DMDs, projection optics, and algorithms for the purpose of rendering images with a high-speed stream of optical bit segments that the eye (actually the human visual system) perceives as high-quality analog images. Because grayscale imaging involves only binary switching, the image quality is exceptionally stable over time.



The hidden hinge DMD was developed in 1994. This translucent mirror rendering reveals the "hidden" structure of one pixel. The micromirror was 16 x 16 microns. (A micron is one millionth of a meter.) The torsion hinge thickness was less than 1,000 angstroms. (An angstrom is one hundred-millionth (10^{-8}) of a centimeter.)



A diagram illustrating how two DMD pixels switch light (left pixel is off, right pixel is on).

The DMD micromirror is mechanically supported by a pair of compliant torsion hinges or flexures. An air gap between the micromirror and the substrate allows the micromirror to freely rotate. Flexible rotation stops or "springtips" limit mirror rotation to ±12 degrees. Two address electrodes are symmetrically placed on either side of the mirror's rotation axis and connected to the "complementary" sides of a static random access memory (SRAM) cell. The voltage that appears on the two address electrodes is (+Va, 0) for memory state "1", and (0, +Va) for memory state "0".

To facilitate electronic switching of the micromirrors between rotational states, a mirror control waveform signal is applied to the mirrors through their common electrical bus. The "bias" voltage level of the mirror control waveform provides sufficient electrostatic attraction between the mirrors and their nearest address electrodes to "latch" the mirrors at one of the limiting rotation angles, ±12 degrees. While the mirrors are latched, the underlying memory cells are updated with new address information that controls whether a mirror will be "on" (memory state "1") or "off" (memory state "0") during the next optical bit segment.

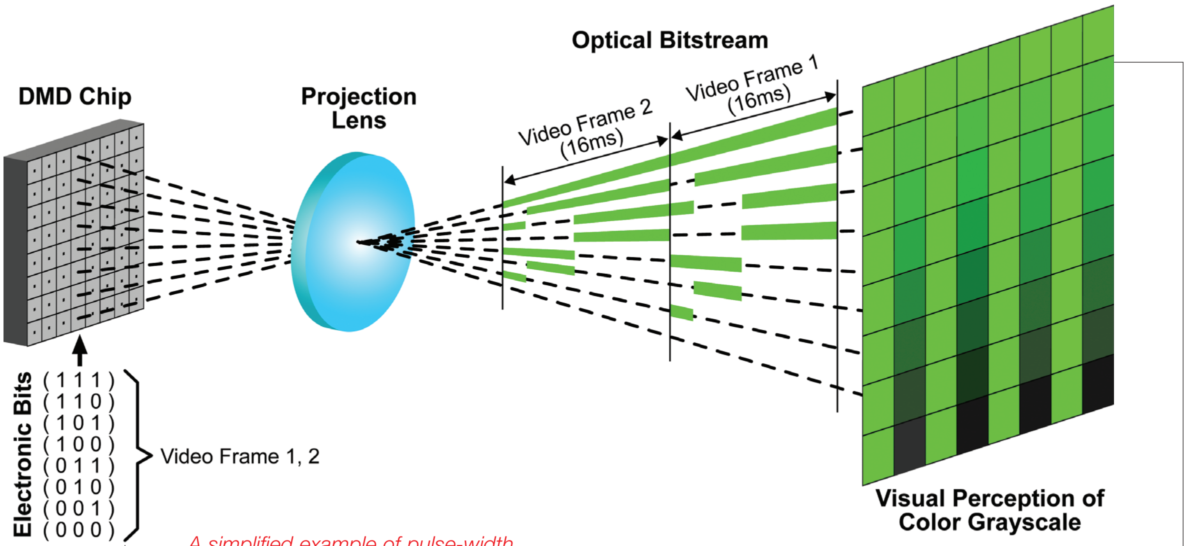
Once the memory cells are updated, a short duration voltage or "reset" pulse is applied to the micromirrors creating a momentarily strong electrostatic attraction of each mirror to its nearest address electrode. The springtips are compressed during the reset pulse and store elastic energy, the amount depending on the voltage drop, between the mirror and its nearest address electrode. For "crossover" mirrors, the voltage drop is greater than for "stay" mirrors, so "crossover" mirrors store more elastic energy in their springtips compared to the "stay" mirrors. Consequently, once the reset pulse has ended and as the stored elastic energy is released, the "crossover" mirrors accelerate away from the address electrode at a greater rate than do the "stay" mirrors.

When the "bias" voltage is reapplied to the mirrors a short time later, the more slowly moving "stay" mirrors are recaptured by the electrostatic field and remain latched in their original rotational state. Meanwhile the "crossover" mirrors have rotated to the opposite rotational state where they are attracted to that address electrode and are latched. With both the "stay" and "crossover" mirrors latched, the memory cells can once again be updated for the next optical bit segment.

In operation, each micromirror reflects incident light either into or away from the pupil of a projection lens so that at the projection screen, the magnified pixel is bright or dark depending on the rotation state of the micromirror. By switching the micromirrors thousands of times a second, an optical bitstream is created and perceived by the eye as analog light. This technique for creating grayscale is called pulse-width modulation (PWM).

To implement PWM, the video frame period is divided into many small discrete time periods called “bit segments.” A mirror may switch the light “on” or “off” during any bit segment according to whether its memory cell was previously loaded with a “1” or a “0.” The eye (actually the human visual system) “averages” over the resulting optical bitstream created by the mirror and perceives the intensity (gray) level as the average fraction of time that the mirror is on. To render high-quality grayscale images, the video frame period of 16 milliseconds is divided into more than 100-bit segments. This corresponds to loading more than 6,000 bits/second/pixel into the memory cell controlling each micromirror.

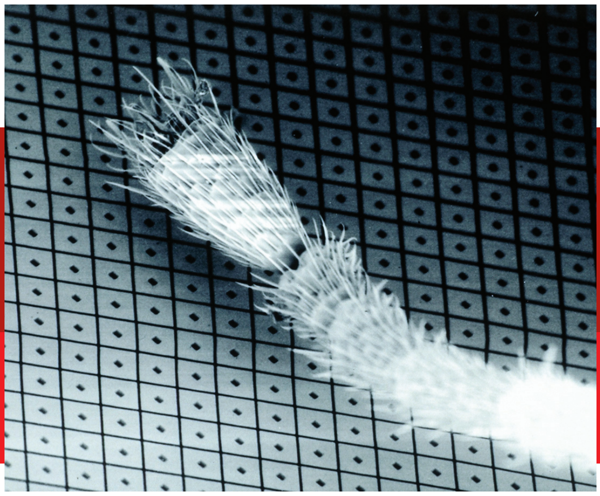
Color is added by one of three methods. For compact projectors and TVs, a single DMD chip is used in conjunction with a high-intensity discharge lamp and rapidly spinning color wheel. For large-venue and digital cinema applications, three DMD chips are used with color-splitting prisms. The third way to add color is by using solid-state lighting systems such as LED (light emitting diodes) or lasers.



A simplified example of pulse-width modulation of light.

This is a simplified example of the pulse-width modulation of light to create the visual sensation of gray levels. A three-bit binary word is input to the DMD (one bit at a time from the most significant to the least significant) into the memory cells of every other column of an 8 x 8 array to create an intensity ramp of green light having seven gray levels plus a black level.

Actual digital light processing systems use a combination of algorithms to create highly realistic grayscale images. For example, gray levels are rendered with eight- to ten-bit words per color, and the longer bit times are split into bit segments and sequenced in time to “homogenize” the optical bitstream.



Photomicrograph showing the tiny micromirrors on a DMD as compared to an ant's leg. These micromirrors switch 5,000 times per second to reflect light and create an image.

Manufacturing

The DMD has a number of advantages over its early deformable mirror ancestor, and one of these is the way it is manufactured. The original deformable mirror device was a hybrid structure consisting of two parts, a nMOS address circuit with air gap spacers formed on a silicon wafer and a metalized polymer membrane mirror formed on a tensioning ring. The two parts were manufactured separately and laminated together in the final step.

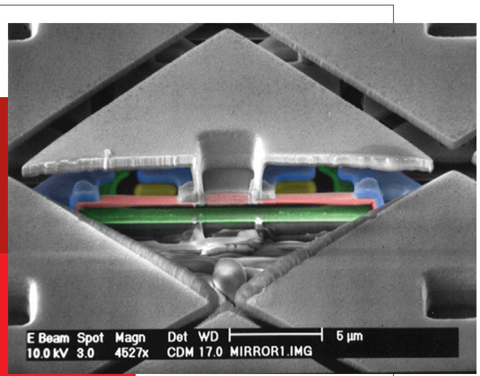
By contrast, the DMD is a monolithic structure. The entire device, beginning with the CMOS address circuit followed by the DMD superstructure, is manufactured on a silicon wafer by a succession of conventional semiconductor process steps that include metal sputter deposition, photolithography and plasma etching.

DMD Superstructure Layers (top to bottom)

5 Metal mirror
4 Second sacrificial photoresist layer
3 Metal torsion flexure (hinge) and raised address electrodes
2 First sacrificial photoresist layer
1 Metal address electrodes
0 CMOS address circuit (transistors and their metalization layers)

The DMD superstructure comprises three layers of patterned aluminum alloys (address electrode, hinge and raised electrode, mirror) alternated with two layers of stabilized photoresist (sacrificial layers). In one of the final manufacturing steps, the sacrificial material is removed by plasma etching to form the air gaps of the superstructure that allow movement of the individual micromechanical elements. To ensure that the contacting surfaces of the DMD do not stick, a self-assembled monolayer lubricant is deposited during the final packaging operation.

A key area of process development for the DMD is the torsion flexure. New alloys had to be developed and understood at the thin-film level. The thickness of the flexure is less than 1,000 angstroms, and at this thickness, the bulk properties of a metal alloy do not necessarily translate to the flexure metal. Of previous concern were metal fatigue due to repeated cycling and metal creep under high-duty-factor operation. However, the aluminum alloy flexures are reliable to more than 5 trillion (5×10^{12}) cycles (the equivalent of more than 200,000 operating hours.)



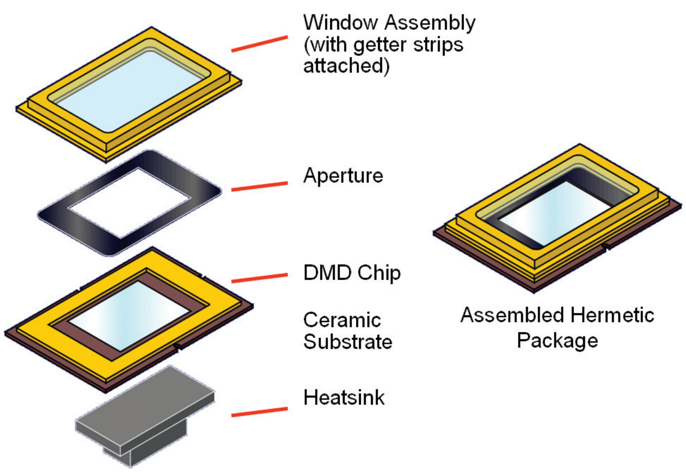
A cross section of a DMD revealed through ion mill sectioning (colorized photomicrograph).] >>

Packaging

A key factor in the DMD's commercial success is the package technology. Many of the package requirements are unique to the DMD and the DLP technology application.

DMD package requirements include:

1. Optical access through a low-defect window
2. Optical aperture to create a dark border around the projected image
3. A package headspace conducive to reliable DMD operation (trillions of cycles over the lifetime of the projector or TV)
4. Temperature control of the DMD chip by removing excess heat created by adsorption of light from the projection lamp

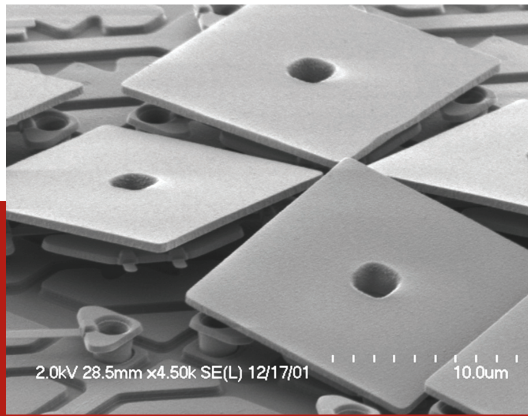


Steps in hermetic package assembly flow include die attachment, wire bonding, getter strip attachment to the window, lubricant deposition, and window assembly welding to the package seal ring.

The headspace requirement was the most difficult one to meet. It drove the package design in two ways. For one, the window seal minimized the incursion of outside contaminants like water. To that end, the window was created by fusing glass to a metal frame. The metal frame was welded to a seal ring brazed onto the top surface of the package substrate. The result was a hermetic seal that completely eliminated any concern of outside contaminates entering and degrading the headspace. Secondly, getter strips capable of adsorbing various impurities in the headspace were attached to the bottom surface of the window to control the head-space chemistry.

As part of the DMD packaging flow, an automated, high-speed wire bonder attaches more than 200 bond wires, first making a "ball" attachment of the wire to the bond pad on the chip, and then making a "stitch" attachment to the lead frame of the package. The wires are made of gold about one-thousandth of an inch (25 microns) in diameter. These bond wires are clearly visible in a previous figure entitled "First hidden hinge DMD (1993)" where the field of view of the projection lens was increased to show the region surrounding the edge of the chip.

It is interesting to note that the first practical, automated production wire-bonder for the assembly of integrated circuits was the Texas Instruments' ABACUS II wire bonder, placed in service beginning in 1973. It had a continuous bonding rate of 6,500 wires per hour compared to a manual bonding rate by a first-class operator of about 1,000 wires per hour. The ASME designated the ABACUS II as a Historic Mechanical Engineering Landmark in 1992.



Photomicrograph of tilted DMD micromirrors (neighboring mirrors are removed to reveal substructure).

Complexity[18]

The DMD is one of the most complex micromachines ever built with more than 1 million moving parts working flawlessly for trillions of cycles. As an example, each micromirror in a projector that operates for 100,000 hours will cycle approximately 2.5 trillion (10^{12}) cycles. If the DMD has 1 million micromirrors, then the total number of cycles for all of the mirrors is 2.5 quintillion (10^{18}) cycles.

In 1992, when large-scale development of the DMD began, knowledge of the DMD's failure modes was extremely limited. No one had ever attempted to develop a micromachine that would remain functional after 10^{18} mechanical cycles and contacts.

Ultimately, the DMD development team chose to use a Failure Modes and Effects Analysis (FMEA) approach. Experts from various disciplines came together to brainstorm possible failure modes. The group considered process techniques, design constraints, equipment limitations, packaging concerns, test issues, and many other potential failure mode contributors. For each failure mode identified, the team documented the potential failure mechanism, the time the failure would most likely occur, possible accelerators of the mechanism, the risk to lifetime or failures, and the test or analysis method used for verification.

Another approach, test-to-failure, was implemented to probe and explore the limits of the DMD. This mandated that the product undergo stresses beyond the thermal, electrical, mechanical, chemical, and optical product specifications. As the tests identified weaknesses, the team evaluated the results to determine if design/process changes were necessary. Over time, DMD robustness improved, providing large margins to failure that could be traded off during future development activities such as the development of DMDs with smaller pixel sizes, larger mirror rotation angles or faster switching speeds.

Bibliography/References

1] L.J. Hornbeck, “128 x 128 Deformable Mirror Device,” IEEE Trans. Electron Devices, No. ED-30, pp. 539-45, 1983.

2] L.J. Hornbeck and W.E. Nelson, “Bistable Deformable Mirror Device,” OSA Technical Digest Series Vol. 8, Spatial Light Modulators and Applications, pp. 107-110, 1988. First paper on digital micromirror device.

3] L.J. Hornbeck, “Current Status of the Digital Micromirror Device (DMD) for Projection Television Applications (Invited Paper),” IEEE International Electron Devices Technical Digest, pp. 381-384 (1993).

4] L.J. Hornbeck, “Digital Light Processing™ and MEMS: Timely Convergence for a Bright Future (Invited Plenary Paper),” Proc. SPIE, Vol. 2639, Micromachining and Microfabrication Process Technology, p. 2, 1995 – Abstract Only. 18-page paper is available at www.dlp.com.

5] R.L. Knipe, “Challenges of a Digital Micromirror Device: Modeling and Design,” SPIE Europto Proceedings, Vol. 2783, pp. 135-145 (June 12-13, 1996).

6] L.J. Hornbeck (invited), “Digital Light Processing™ for High-Brightness, High-Resolution Applications,” Proc. SPIE, Vol. 3013, Projection Displays III, pp. 27-40 (1997). Contains a comprehensive set of DMD and DLP® references.

7] L.J. Hornbeck, T. Russ Howell, R.L. Knipe, and M.A. Mignardi (invited), “Digital Micromirror Device – commercialization of a massively parallel MEMS technology,” ASME Symposium on Micromechanical Systems: Devices and Applications, DSC-Vol. 62, pp. 3-8, 1997. First paper addressing the commercialization issues of DMD.

8] P.F. van Kessel, L.J. Hornbeck, R.E. Meier and M.R. Douglass, “A MEMS-Based Projection Display,” Proceedings of the IEEE, Special Issue: Integrated Sensors, Microactuators, and Microsystems (MEMS), Vol. 86, No. 8, pp. 1687-1704 (Aug. 1998).

9] M.R. Douglass, “Lifetime estimates and unique failure mechanisms of the Digital Micromirror Device (DMD),” IEEE International Reliability Physics Symposium Proceedings, pp. 9-16 (1998).

10] L.J. Hornbeck, “From Cathode Rays to Digital Micromirrors: A History of Electronic Projection Display Technology,” Texas Instruments Technical Journal, Vol. 15, No. 3, pp. 7-46 (July-September, 1998). Also published at www.dlp.com. A comprehensive review of electronic projection display technology.

11] L.J. Hornbeck, D. Darrow, G. Pettitt, B. Walker, W. B. Werner, “DLP Cinema® Projectors: Enabling Digital Cinema,” 2000 SID International Symposium Digest of Technical Papers, Vol. XXXI (2000), pp. 314-317.

12] Mignardi, M.A., Gale, R.O., Dawson, D.J., Smith, J.S., “The Digital Micromirror Devices – A Micro-Optical Electromechanical Device for Display Applications,” MEMS and MOEMS Technology and Applications, P. Rai-Choudhury, editor, SPIE Press, 2000. Chapter 4, Page 169.

13] M. Douglass, “DMD Reliability: a MEMS Success Story (Invited Paper),” Proceedings of the SPIE, Vol. 4980, pp. 1-11 (January, 2003).

14] Dan Morgan, “Designing Front Projectors with DLP® Technology,” SID Proceedings of the First Americas Display Engineering and Applications Conf., pp. 182-185, October 26-27, 2004.

15] Gary Sextro, “Image Quality Trends in Home Entertainment DLP® TVs,” SID Proceedings of the First Americas Display Engineering and Applications Conf., pp. 186-188, October 26-27, 2004.

16] Michael R. Douglass, “Development of the Digital Micromirror Device (DMD) Microsystem (Invited Paper).” Proceedings of the DCMM Symposium on Mechatronics and Microsystems, pp. 17-24 (September, 2005).

17] L.J. Hornbeck, “Combining Digital Optical MEMS, CMOS, and Algorithms for Unique Display Solutions (Plenary Paper),” IEEE International Electron Devices Technical Digest, pp. 17-24 (2007).

18] M.R. Douglass, “MEMS Reliability – Coming of Age (Keynote),” Proceedings of the SPIE, Vol. 6884, 688402 (2008).

The History and Heritage Program of ASME

The History and Heritage Landmarks Program of ASME (the American Society of Mechanical Engineers) began in 1971. To implement and achieve its goals, ASME formed a History and Heritage Committee initially composed of mechanical engineers, historians of technology and the curator of mechanical engineering at the Smithsonian Institution, Washington, D.C. The History and Heritage Committee provides a public service by examining, noting, recording and acknowledging mechanical engineering achievements of particular significance. This Committee is part of ASME's Center for Public Awareness. For further information, please contact Public Awareness at ASME, Three Park Avenue, New York, NY 10016-5990, 1-212-591-7020 and http://www.asme.org/history.

Designation

Since the History and Heritage Program began in 1971, nearly 250 landmarks have been designated as historic mechanical engineering landmarks, heritage collections or heritage sites. Each represents a progressive step in the evolution of mechanical engineering and its significance to society in general. Site designations note an event or development of clear historic importance to mechanical engineers. Collections mark the contributions of a number of objects with special significance to the historical development of mechanical engineering.

The Landmarks Program illuminates our technological heritage and encourages the preservation of the physical remains of historically important works. It provides an annotated roster for engineers, students, educators, historians and travelers. It helps establish persistent reminders of where we have been and where we are going along the divergent paths of discovery.

Founded in 1880 as the American Society of Mechanical Engineers, ASME is a not-for-profit professional organization promoting the art, science and practice of mechanical and multidisciplinary engineering and allied sciences. With more than 127,000 members worldwide, ASME is a global engineering society focused on technical, educational and research issues. ASME develops codes and standards that enhance public safety, and provides lifelong learning and technical exchange opportunities benefiting the engineering and technology community.

ASME

Sam Y. Zamrik, Ph.D	President
John Hawkins, P.E.	District Leader
Robert Luna, P.E.	Senior Vice President
Capt. Vincent Wilczynski	Vice President
Virgil R. Carter, FAIA	Executive Director

ASME HISTORY AND HERITAGE COMMITTEE

J. Lawrence Lee, P.E.	Chair
Robert Casey	
Robert Friedel	Chair, Plaque Sub-committee
R. Michael Hunt	Immediate Past Chair
Richard I. Pawliger, P.E.	Chair, Brochure Sub-committee
Mark Powell, P.E.	
Paul J. Torpey	Past President
Herman Viegas, P.E.	
John K. Brown	Corresponding Member
Robert O. Woods, P.E.	Corresponding Member
Marina Stenos	Director, Public Awareness and Leadership & Diversity
Edward Kudlis	Coordinator, Centers Projects

ASME DISTRICT E

Austin Kozman	Section Chair, North Texas Section
Jeff Schroeter	History and Heritage Chair, North Texas Section
Bogdan Antohe	Banquet and Special Events Chair, North Texas Section

Texas Instruments

Tom Engibous	Chairman
Rich Templeton	President and Chief Executive Officer
John Van Scoter	Senior Vice President and General Manager, DLP® Products
Kevin March	Senior Vice President and Chief Financial Officer
Kevin Ritchie	Senior Vice President, Technology and Manufacturing Group
Terri West	Senior Vice President and Manager, Communications and Investor Relations

Acknowledgements

Special recognition and thanks go to Mark Fletcher, Frank Poradish, Mike Guillory, Douglas Darrow and Steve Gumm for their work in the nomination process and to Larry Hornbeck and Amy Treece for writing the brochure. Thank you also to Actuality Systems for the use of the Perspecta® Spatial 3D photo.

TEXAS INSTRUMENTS

Mixed Sources
Product group from well-managed forests, controlled sources and recycled wood or fiber
www.fsc.org Cert no. XXX-XXX-000
© 1996 Forest Stewardship Council

dlp.com

DLP0350