# From cathode rays to digital micromirrors: A history of electronic projection display technology

*Abstract: In the late 1800s it was called "distant electric vision" or the "electric telescope," words to describe mankind's dream to see instantaneously beyond the horizon with electric technology. Today we use the word television. The early window for seeing beyond the horizon was the cathode ray tube or CRT, first demonstrated in crude form in 1897 and developed as a "practical" window in 1929. In the late 1940s following World War II, motion picture studios in concert with the fledgling television industry sought to bring live programming to the movie theater audience. This was the birth of "big-screen" electronic projection display technology. Projection CRTs led the way, but soon, the forerunner of the modern laser display as well as the first spatial light modulator or "light valve" made their commercial debuts.*

*Over the following 50 years, the display industry has searched for the ultimate big-screen technology, not only for the theater, but also for the trade show, classroom, boardroom and living room. An ingenious and sometimes bewildering array of projection technologies has been developed, with the goal of producing brighter, higher fidelity images with displays having lower weight and cost. This article describes those technologies as they evolved, beginning with the early ones based on the CRT and e-beam addressed oil films and continuing to the present day technologies of improved CRTs, scanned laser beams, the liquid crystal display (LCD), and culminating with the all-digital technology Digital Light Processing™ (DLP™) based on the Digital Micromirror Device™ (DMD™).*

Mankind's early fascination with the viewing of life-like moving images led to the development of a variety of optical gadgets in the 19th century. One of the earliest was the phenakistoscope, a set of phased drawings mounted on a twirling disk (circa 1832). With the invention of the positive photographic process in 1839 by Daguerre, the drawings were replaced with a succession of phased photographs.

These optical toys were based on the understanding that a closely spaced series of images could be used to portray a sense of time and motion. This entertainment curiosity was intriguing enough to become a popular and rather sizeable niche business, although the subject or content of the flipping images was of little creative value. Revenues were limited by the fact that only one person could view the images at a time by peering into an eyehole.

It was not until the invention of the motion-picture camera, or "Kinetograph," in 1887 by Thomas Alva Edison, (or his assistant Dickson, as some would argue) that a continuous set of photographic images could be generated. An adjunct to the Kinetograph was a single-viewer apparatus called the "Kinetoscope." During an exhibition in Paris, a Kinetoscope demonstration inspired the Lumiere brothers, Auguste and Louis, to invent the first commercially viable film projector, the "cinematographe." The first public screening using this new technology was in Paris on December 28, 1895. This event is generally regarded as the birth of the "cinema."

Film projection technology enabled a new business model based on a large (paying) audience who could simultaneously view the same content, thereby allowing higher revenue potential than the early single-viewer novelties. This fueled the creative passions of the early movie moguls, who founded the movie entertainment business, using photographic film as their capture and display medium. Beyond the increased profit potential, projection technology enabled a large audience to view a motion picture together as a "shared experience," enhancing the enjoyment in much the same way as when people experience a symphony, play, sports or other group entertainment.

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Film-based projection technology has its limitations, however, including its inability to provide live content to the audience, the expense of the film prints (including transportation costs) and their inexorable deterioration with repeated screenings. Electronic projection display technology provides an answer to these shortcomings, but the stimulus for its development had to await the age of commercial television.

The grandfather of electronic displays, the CRT or cathode-ray tube, was invented more than 100 years ago. In spite of its age, the CRT is still the dominant display technology today. In the 1940s motion picture studios and the youthful television industry sought to bring live television programming to the theater by using electronic projection technology, but the CRT lacked the necessary brightness. The so-called "light-valve" technologies were developed primarily for sports-driven display venues. In other, less demanding applications, the CRT remained dominant because light-valve technologies were too expensive, bulky and heavy.

But recently, new light-valve technologies are replacing both the CRT and the older first- and second-generation light valves in high-brightness display venues. And because these new light-valve technologies can be designed into more compact products, their availability has opened up new market opportunities where low weight and portability are required. Perhaps soon, the CRT will be replaced in high-end consumer projection display products for the home as well.

The projection CRT's longevity can be attributed to several factors. First, although the projection CRT is considered a "mature" technology, it has been steadily improved over a long period and incremental improvements are even being made today. And second, until recently light-valve technologies were unable to take full advantage of the economies and stability offered by the digital electronics revolution. This digital age has brought us such advanced services and products as the Internet, digital satellite TV, digital cell phones, CD audio, the digital video disc (DVD) and others.

Another popular display technology today, the liquid crystal display (LCD) has been partially successful in replacing the CRT in certain projection display venues. But LCDs have traditionally been fabricated on glass and more recently on quartz. Integration with single-crystal silicon, the stuff that has fueled the semiconductor electronics industry revolution, has been difficult and only recently have such LCD products emerged. These display, as well as the CRT, are still ultimately based on analog technology at the modulated light level and subject to analog limitations.

What has been lacking until recently is a projection technology without any analog links in the electronic chain between source material and viewer—a true all-digital display. This technology would be monolithically integrated on a digital chip. It would present a bright, flicker-free, seamless image to the eye, with the characteristics that we have come to expect from digital technology, namely high image fidelity and stability. The display would exhibit no lag or smearing of the image from one digital frame to the next.

In fact, such a technology has recently been commercialized. Silicon-based digital technology combined with new materials and processes allows, for the first time, the monolithic integration of an efficient digital light switch with a digital address chip to produce a fast digital projection display. This technology, invented and developed at Texas Instruments, is called the Digital Micromirror Device (DMD). Digital Light Processing (DLP) projection systems based on the DMD have outstanding image fidelity combined with inherent digital stability and noise immunity. In 1998, only two and one-half years after product introduction, DLP projection systems have achieved acclaim from customers and industry experts alike, with more than 100,000 systems sold to date.

The story of how the display industry evolved from cathode rays to digital micromirrors is both illuminating and complex. In what follows, we will simplify for the sake of clarity and brevity. Representative papers in the reference section give further details.

## Distant electric vision and the CRT

Our dream to see instantaneously beyond the horizon with electric technology had its origins in two 19th century inventions, the telegraph and the telephone. Samuel F. B. Morse, using his telegraph, demonstrated the first successful communication at a distance with electricity in 1837. The telegraphic code, consisting of dots and dashes, provided a crude means for communicating with words. Soon several inventors came up with schemes for using the telegraph to transmit copies of writing and designs. These ideas were based on synchronized rotating cylinders at the transmitting and receiving end and metal styluses that traced a spiral path across the

cylinders. Alexander Graham Bell invented the "speaking telegraph" or telephone in 1876. The intimacy of spoken communication provided a powerful stimulus to devise methods for communicating instantaneously with images as well.

Beginning in the 1870s there were numerous schemes proposed for "seeing" beyond the horizon (*Figure 1*) and they were given the names "distant electric vision," "electric telescope," "telectroscope," and "telephot." It was not until 1900 that distant electric vision received the name that we recognize today, "television." Constantin Perskyi first used this word in a paper read at the International Electricity Congress held in connection with the 1900 Paris Exhibition. Twenty-eight years later C.P. Scott, editor of the *Manchester Guardian,* wrote "Television? The word is half Greek and half Latin. No good will come of it."
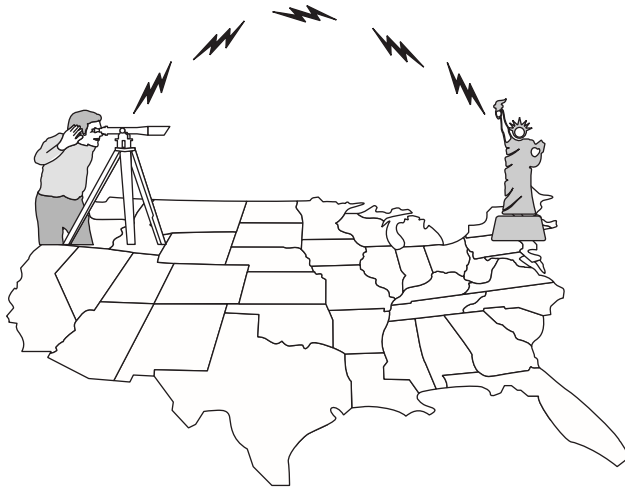


**Figure 1.** Electric telescope, circa 1886.

While inventors were dreaming up schemes for distant electric vision, groundwork was being laid for the invention of the cathode ray tube (CRT), the device that would be the first window for seeing beyond the horizon. From 1858 to 1897 a host of researchers, including Geissler, Crooks, Fleming and Thomson, discovered "cathode rays" and demonstrated their properties. They showed how to produce cathode rays in low-pressure discharge tubes; how to focus, accelerate and deflect them; and finally how to convert these rays into light by slamming them into phosphor and causing the phosphor to emit light. A Crook's tube, shown in *Figure 2*, demonstrated the fact that the mysterious rays came from the cathode. We now know that cathode rays are actually electrons.
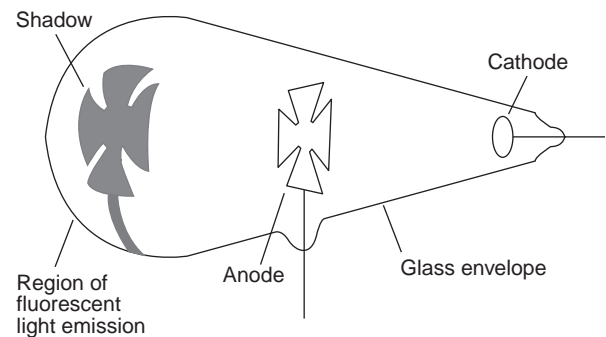


**Figure 2.** Crook's tube.[1]

In 1897 Ferdinand Braun took the ideas of his predecessors and constructed a tube that was named after him and became the forerunner of the modern CRT. He devised a way to define the cathode rays into a pencil-like beam by passing the rays through an anode aperture. He covered the end of the tube with a fluorescent material that gave off light when struck by the high-energy electrons. The Braun tube was magnetically deflected in one dimension, and by viewing the tube through a rotating mirror it was first used as an oscillograph to study electrical waveforms.

Improvements to the Braun tube, or CRT, continued and by 1907 it was sufficiently advanced to be incorporated into a patent application by Boris Rosing for a complete television system. The television camera consisted of an optomechanical scanner. On the receiving end was a Braun tube modified to permit deflection of the beam in both the horizontal and vertical directions, as well as a means of modulating the intensity of the electron beam. A way to synchronize the mechanical scanner and CRT was also provided.

Vladimir Zworykin, a student of Boris Rosing, was later to develop the first practical CRT for home television use while an employee of Westinghouse Research Laboratories. Zworykin delivered a paper on November 18, 1929, to the Institute of Radio Engineers at Rochester, New York, describing his new "Kinescope" or CRT, shown in *Figure 3*. It included a means of focusing the light by using an electrostatic "lens."[2]

Albert Abramson writes in the history of television, 1880 to 1941: "The disclosure of the Kinescope changed the history of television. Zworykin's tube was the most important single technical advancement ever made in the history of television."[3]
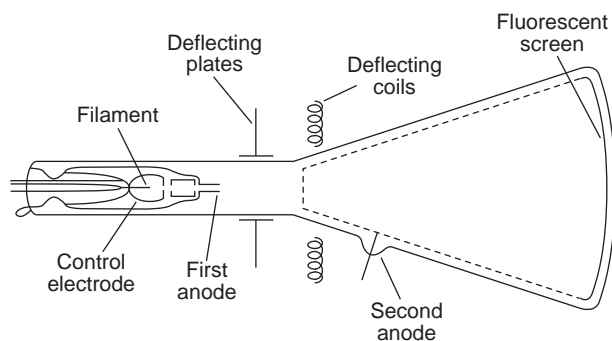
**Figure 3.** Zworykin's 1929 Kinescope (CRT).[1]

Later, Zworykin was to join the Radio Corporation of America (RCA) where he would introduce a new, all-electronic camera tube called the Iconoscope. The Kinescope, together with the Iconoscope, would enable RCA to demonstrate an improved all-electronic television system in 1933.

For a detailed history of early television, the reader is directed to two books written by Abramson.[1,3]

## Early electronic projection displays

In the United Kingdom the London Television Service began regular commercial television broadcasting in 1936. However, in the United States commercial television was delayed because of an absence of broadcast standards. In 1941 the National Television Standards Committee (NTSC) finally adopted standards for the U.S., and the American television industry was launched. The blossoming of this new industry was hindered as the United States entered World War II. During the war, RCA built a huge CRT manufacturing facility with Navy financing to support the war effort. More than 20 million tubes were manufactured there for military applications. Soon after the war, RCA began to manufacture 10-inch television sets that sold for $375, expensive considering the value of 1945 dollars relative to today! At the beginning of 1949, television was attracting 19 percent of the broadcast audience, and by December more than 41 percent!

The motion picture industry began to feel threatened by the burgeoning television audience. It was true that television receivers in the home had small picture tubes and were expensive. However, there was growing concern in the late 1940s about the growing popularity of television receivers in local bars, where patrons were flocking to see sporting and

other live events. If electronic projection displays could be developed for the motion picture theater screen, live television broadcasts of news and sporting events could be displayed in ordinary theaters on large screens for the movie-goer's enjoyment. Live programming could even be mixed with conventional movie presentations. The expectation was that film-based theaters could eventually be replaced by video theaters, provided electronic projection technology could be developed to deliver film-like images. Today, ironically, theaters are still film-based in an era when films are distributed electronically via digital satellite TV and the digital video disc! Perhaps new digital projection technology based on the DMD will finally provide the means to fulfill this expectation after more than 50 years.

Three technologies were developed in the early 1940s for the projection of television images inside a movie theater, namely, the CRT with Schmidt optics, the Eidophor and the Scophony. These technologies were early representations of the three modern-day classes of projection displays, the CRT, "light-valves" and laser projectors.

***The CRT Projector***—On May 7, 1940, RCA demonstrated its large-screen projection television system based on a CRT and very efficient Schmidt reflective optics. Although the images were only 4.5 x 6 feet, the *New York Times* declared "Projection 'Gun' Shoots Televiews: The Aim is to Hit a Theater Screen."

RCA's Schmidt optics projection system is shown in *Figure 4*. In this system the CRT faces away from the projection screen. It is driven to maximum brightness and the light is collected by a spherical mirror and projected onto the screen through an aspherical corrector lens.
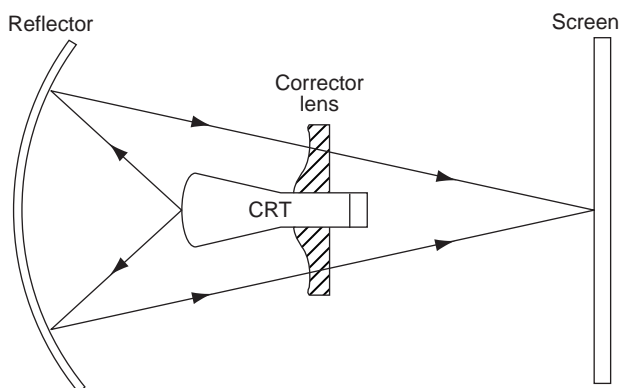
**Figure 4.** CRT projection system with Schmidt optics.[4]

On May 9, 1941, one year after its initial large-screen demonstration, RCA demonstrated a larger version of its new projector at the New Yorker Theater, where the Soose-Overlin prize fight from Madison Square Garden was displayed live on the big screen. This new system had a 7-inch diameter CRT. The Schmidt projection optics employed a 30-inch mirror and operated at an optical magnification equal to 45x. The projected screen image had a diagonal of 26 feet but only half the brightness of conventional film projectors today, even though the screen had a 5x forward gain.

***The Eidophor***—Clearly, the CRT projector was not going to be practical for the large screens found in a typical movie theater. Interestingly, Professor Fritz Fischer, head of the Technical Physics Department at the Swiss Federal Institute of Technology in Zurich, had been studying this problem even before the demonstration by RCA in the New Yorker Theater. He published his findings under the title "A Study on the Feasibility of the Cathode Ray Tube with Fluorescence Screen for the Television Projection in Movie Theaters."

The light output of a projection CRT was limited (and still is today) by the capability of the electron gun to maintain focus at high currents and by phosphor saturation. Fischer believed that a new approach to high-brightness projection displays was required. What he proposed was the first spatial light modulator or light-valve technology. In a light-valve technology, the functions of light generation and light control are separated.
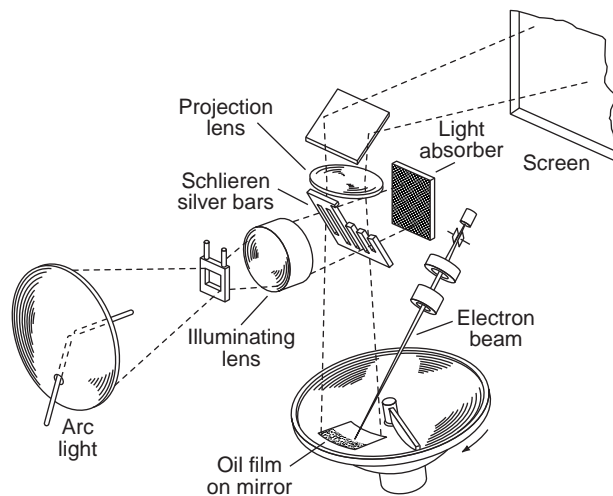
In November 1939 he applied for a patent for an ingenious light-valve technology based on a thin oil-film control layer. The light valve was later given the name Eidophor or image bearer (in classical Greek, image is "eido" and bearer is "phor"). *Figure 5* shows the Eidophor projection system. A thin oil film is spread on the surface of a conducting and reflecting spherical-shaped substrate and addressed by a rastered electron beam. As the e-beam scans the oil surface, it deposits a charge pattern, as shown in *Figure 6*. The charge pattern is electrostatically attracted to the conducting substrate and causes a deformation pattern in the oil that, in turn, acts as a phase diffraction grating.
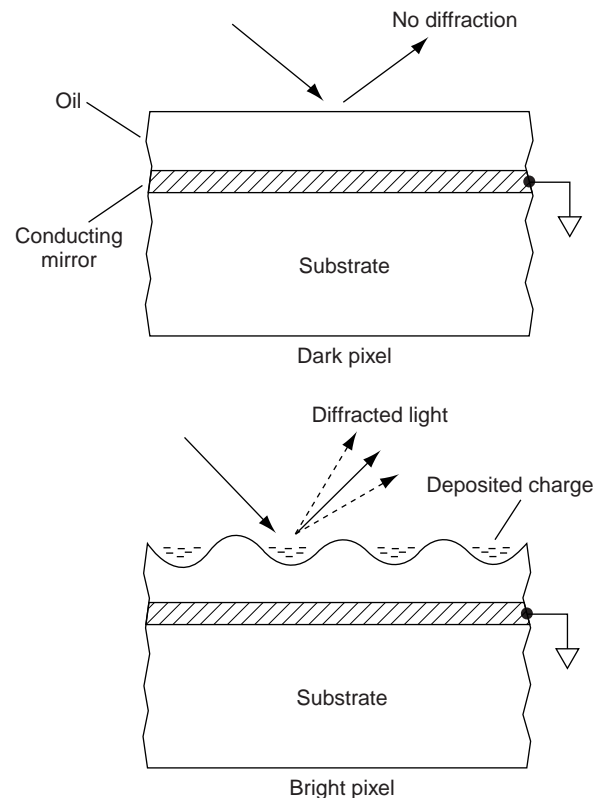


**Figure 6.** Principle of Eidophor operation.

Light from an arc lamp is focused onto the oil surface after being reflected from a set of silvered "Schlieren" bars (or light stops). For the first pixel of Figure 6, no charge has been deposited and the oil surface is flat. The light passes through the transparent oil film, is specularly reflected from the spherical substrate, focused back onto the bars and then reflected from the bars into the arc lamp. In this case, no light gets to the projection lens and that pixel



**Figure 5.** The Eidophor system (third prototype).[5]

appears dark. For the second pixel of Figure 6, a charge pattern has been deposited, which in turn produces a phase grating in the oil. Light is diffracted by the grating and no longer focuses on the Schlieren bars. Some of it passes through the slots and is imaged onto the screen by the projection lens. In this case, the pixel appears bright. Intermediate brightness levels are achieved by controlling the amount of deposited charge between zero and a maximum level.

The oil film is made conductive with its resistivity and thickness carefully controlled so that the charge from one video field decays before charge for the next is written.

Late in 1943 Professor Fischer demonstrated a prototype Eidophor. The first prototype had many shortcomings, and a second version was begun under Fischer's direction until his untimely death in 1947. Work continued and a second prototype was demonstrated in 1948 with much improved results. Gretener A.G. (GRETAG) commercialized this technology in the early 1950s. Color projection was first implemented with time-multiplexed color and later with three separate units, each projecting a primary color image. The Eidophor has a long and successful history as a very bright electronic projection display technology for auditorium, theater and other large-venue applications. Many units are still in operation around the world today.

An innovative variation of the Eidophor for color projection was invented in 1958 by William E. Glenn at General Electric. Called the Talaria, this oil-film projector uses a single electron gun to write three diffraction gratings, one for each primary color, on a single oil-film surface. This provides a more compact color projection system than the three-gun Eidophor system. Product shipments began in 1968, and like the Eidophor it has achieved a long period of commercial success.

Numerous papers and a book have been written on the Eidophor and the Talaria.[5-11]

*The Scophony Projector*—Scophony Ltd. of England began the development of a projection display system that was first demonstrated in July 1936. In some respects, this early projection technology bears resemblance to the modern laser projector.

A laser projector consists of a laser beam whose amplitude is modulated by a video signal using an acousto-optic modulator. The beam is then mechanically scanned in the horizontal and vertical directions to form an image on a projection screen. The Scophony projector employed scanning in the vertical direction and it used a very clever acousto-optic modulator scheme for both the modulation function and the horizontal scanning function.

*Figure 7* shows how a single line of video is produced at the screen by the original Scophony projector.[12] Light from the arc lamp passes through an acousto-optic modulator consisting of a glass-sided cell filled with a transparent liquid and fitted with a piezoelectric quartz crystal at one end. The video signal modulates an ultrasonic carrier signal that drives the input to the quartz crystal. The crystal vibrations launch acoustic waves in the liquid whose amplitude depends on that of the video signal. The acoustic waves act to produce a variable amplitude phase diffraction grating.
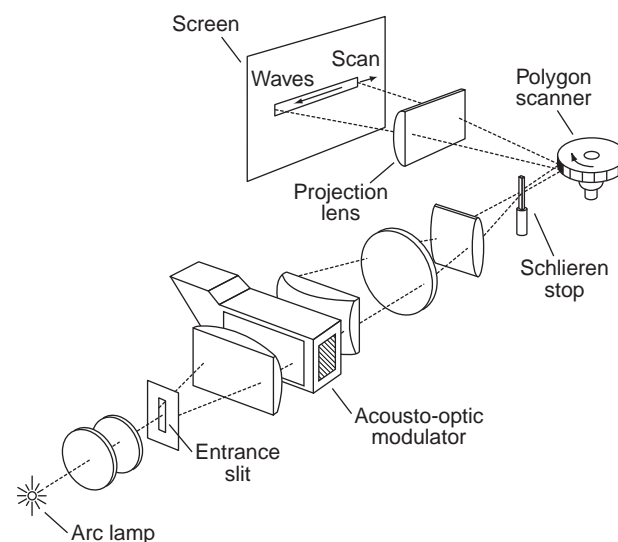


**Figure 7.** Scophony projection system (vertical scanner not shown).[12]

Using the same principle as the Eidophor, the grating diffracts light around an optical (Schlieren) stop, and an image is produced that moves at the speed of sound in the liquid. A counter-rotating polygon mirror freezes the moving line image so that it appears stationary at the screen. A second rotating polygon mirror scans the line image vertically to produce the complete image of the video frame. By integrating the light from one line of video at a time on the screen, the rather dim carbon arc lamps could be made to produce brighter images than if a single spot had been scanned, as in today's laser projectors.

On January 15, 1941, at its New York City head-quarters, Scophony Ltd. demonstrated an improved projector on a 12 x 9-foot rear projection screen. The Scophony projector was never widely adopted. However, Scophony modulation is used today in high- power laser projectors to improve the coupling efficiency and to avoid thermal overload in the acousto-optic modulator.[13]

## CRT projectors—a story of continuous evolution

The CRT has continuously evolved since Vladimir Zworykin's 1929 demonstration of his Kinescope. So-called "electron optics" for focusing the beam on the phosphor is achieved either electrostatically, magnetically, or by using a combination of both techniques. *Figure 8* shows a simple magnetically deflected CRT.
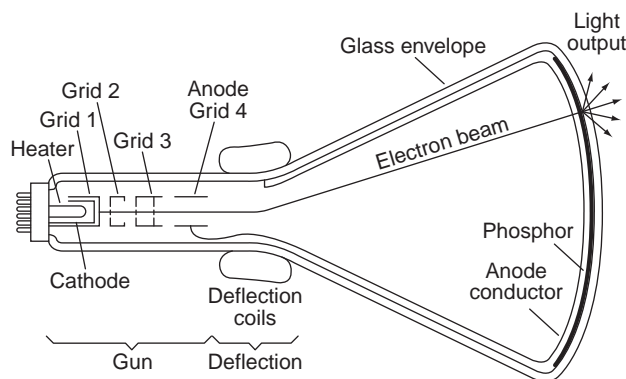


**Figure 8.** Magnetically deflected CRT.[14]

Of the three technologies that were available for large-screen projection in the 1940s (CRT, Eidophor, and Scophony), only the CRT had the potential for home applications because of its cost advantages. For high-brightness applications in which cost was a lesser issue, the Eidophor and later improved light valves were the technologies of choice. In the late 1940s development was under way to put the projection CRT in the home. But these systems had low brightness and when larger direct-view CRTs became available, interest declined in the CRT projection approach.

In 1972 the Advent Corporation introduced a three-tube color projection system having a 7-foot screen that dwarfed direct view television screens.[15] This new technology is believed by many to have renewed public interest in projection television. The three tubes (one for each primary color) had internal, reflective Schmidt optics that yielded high light-collection efficiency. A folded optical design enabled the integration of the three tubes, along with a front projection screen, into a single cabinet. A new screen design provided forward gain that directed more light to the viewer.

Soon Advent and others introduced less costly projection systems based on aspherical, refractive plastic optics that were placed in front of each tube.[16] Today the common configuration for both front and rear projection CRT displays is the in-line system with refractive optics,[17] shown in *Figure 9*. The in-line projection configuration places the two outer tubes at an angle with respect to the screen. This results in both a keystone and a nonlinear scan line distortion that must be corrected electronically.[18] For consumer applications the tube diameter is commonly seven inches, while for commercial projectors and for high-definition applications it is nine inches.
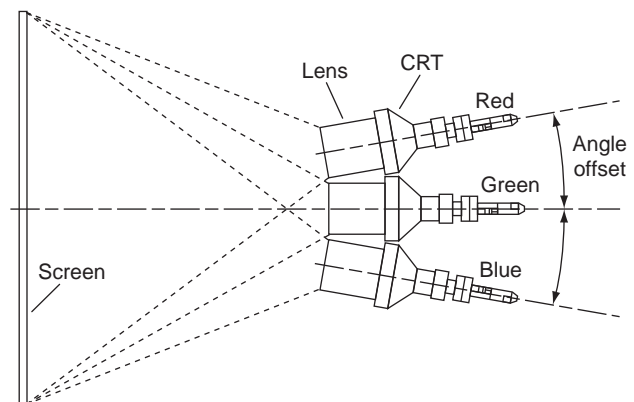


**Figure 9.** In-line projection CRT display.[17]

Convergence of three color images on the screen has been a historical problem. In the beginning, registration was accomplished manually by tediously adjusting numerous convergence controls. The problem is exacerbated for high-definition displays. Now automatic convergence is achieved with photosensors and a microcontroller.[19]

A sustained effort by the projection tube manufacturers has been directed at simultaneously increasing brightness, resolution and color saturation while limiting cost, volume, tube weight and, at the same time, preserving phosphor life.[20] This has often been a frustrating endeavor!

The CRT has one fundamental advantage over light-valve technologies, peak brightness. It can be

briefly overdriven to produce brightness levels for local highlights that are far in excess (up to 5x) of the large-area brightness. The word used to describe the resulting sensation is "punch." For light valves, the local- and large-area brightness levels are equal, because the light is simply being "valved" to varying levels of brightness.

CRT projection display development has continued on a broad front with constant performance improvements from year to year. Historically, CRT projection technology has dominated the home consumer, projection television market from its beginning. But will the new light-valve technologies begin to make inroads against the CRT in this market? They will if they can deliver superior performance at comparable cost and with reduced weight and volume. The gradual shift to high-definition displays in the consumer market may make it increasingly difficult for the projection CRT to maintain its market dominance.

## Laser projectors

The laser was first demonstrated in 1960 and was called by many an "invention looking for a job." It has since found applications from manufacturing and range-finding to surgery, laser printing and projection displays. Its advantage for many applications, including that of the laser display, has been its ability to put a large amount of optical power into a very small spot size.

A recent laser projector design[21,22] is illustrated in *Figure 10.* It consists of red, green and blue laser beams modulated by a video signal and mechanically scanned in the horizontal and vertical directions to produce an image on a screen.
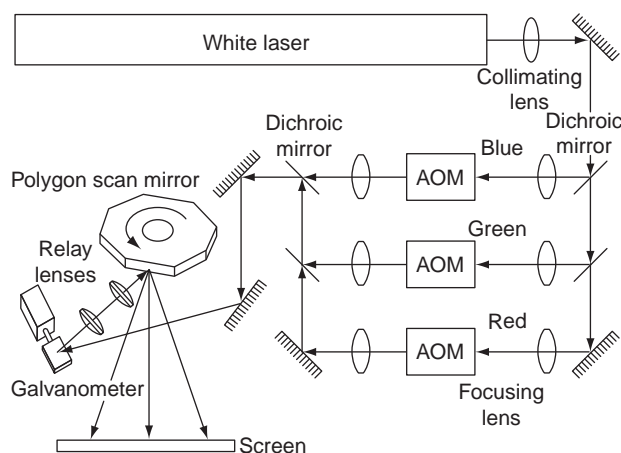


**Figure 10.** Laser projection display.[21]

Light from a krypton-argon white-light laser is separated into its red, green and blue components by dichroic beam splitters. The red, green and blue beams then pass through acousto-optic modulators. The video signal is decomposed into its components (R,G,B) and each component is input into its corresponding modulator. The amplitude of the video signal modulates a high-frequency carrier that sets up acoustic waves in a crystal. The acoustic wave causes diffraction of the light passing through it proportional to the video signal amplitude. The diffracted light beam is amplitude-modulated with the video waveform and the undiffracted light is blocked from the optics path.

The three modulated light beams are combined by dichroic mirrors into a single beam. This beam is steered to a mechanical scanner that consists of a galvanometer-driven mirror for the vertical or frame-scan direction and a rotating polygon mirror for the horizontal or line-scan direction.

One annoying artifact produced by a laser projector is called "speckle" or scintillation of the image. Because laser light has spatial coherence, wavefronts of the light that are reflected back from the screen can interfere with one another, causing a scintillation effect. Speckle can be reduced by using certain types of screen material, vibrating the screen or adding a fixed "bias" level of light to the image reflected from the screen.[23] Of course, the latter method reduces contrast ratio.

One unique advantage of laser displays is their infinite depth of field, which allows the displayed image to be viewed on curved surfaces. Examples include hemispherical-screen theaters or planetariums, uneven or tilted surfaces, buildings, and moving surfaces such as water screens. They are expensive but find application in simulators, amusement parks and special effects shows. To date, the lack of low-cost laser sources and scanners has prohibited the laser display from being used in the consumer projection television market.

## The light-valve technology matrix

The third category of projection display technology is the light valve, for which the Eidophor, discussed earlier in this article, is the archetype.

The Eidophor was the first commercially successful light-valve technology. Because of its success, the Eidophor inspired numerous attempts to develop light valves that were more efficient, compact, less expensive and weighed less. (A modern Eidophor

weighs more than 1000 pounds, excluding the electronics and power supply for the xenon arc lamp.)

The creative energy that went into the effort to develop an alternative light-valve technology is truly remarkable. The variations are so numerous that some way of organizing these technologies in a chart is useful before giving examples. Light valves are also known as spatial light modulators (SLMs), because their function is to take incoming unmodulated light and to modulate the light according to the position in the x-y plane of the SLM.

Light valves are categorized in *Figure 11* according to address technology, the light-valve (or control-layer) technology and whether or not a converter is required. The address technology may be a charge input from a modulated and rasterized e-beam such as the one used in the Eidophor to address the oil film or from a charge-coupled device (CCD). It may be an optical input such as the modulated light from a CRT or a scanned laser beam. The address technology may be electrical in nature, such as an x-y matrix of electrodes that is either passive or active. The active matrix contains a transistor switch at the intersection of each row and column electrode.

Converters are sometimes required between the address structure and the light valve. The photoconductor performs an optical-to-voltage conversion. The pin-grid matrix performs a charge-to-voltage conversion. The photocathode/microchannel plate converter consists of two stages. The photocathode performs an optical-to-charge conversion, and the microchannel plate acts as an electron multiplier to enhance the effective light sensitivity.

Numerous light-valve or control-layer technologies are listed in Figure 11. The oil film control layer has been described in conjunction with the Eidophor and the Talaria. The acousto-optic light valve has been described as it applied to the Scophony and the laser projector.

As shown in *Figure 12*, the light-modulating property varies with the type of light valve. The control layer may randomly scatter light, or a periodic pattern may be developed within each pixel of the control layer to diffract light. The control layer may change the direction of polarization, or it may act to beam steer or defocus the light.

Some of the control layers attempt to directly mimic the Eidophor oil-film control layer by providing another way of producing an addressable diffraction grating. Examples are the elastomer control layer, the micromechanical grating and certain classes of diffractive liquid-crystal light valves. We begin with a description of the elastomer light valves.

## Elastomer light valves

Elastomers are a flexible organic polymer material and have long been regarded as good solid state replacement candidates for the fluid control layer used in the oil-film projectors. Elastomer light valves have been demonstrated with metal electrode,[24-26] e-beam[27] and optical addressing.[28,29] An elastomer with metal electrode addressing is shown in *Figure 13* to illustrate the basic principle of operation. Two pixels are shown, one energized and the other non-energized.

The elastomer is metallized with a thin reflecting layer that serves as both a mirror and a counter-electrode. A voltage is placed on every other address electrode of the addressed pixel to produce a deformation pattern. The elastomer is squeezed by the
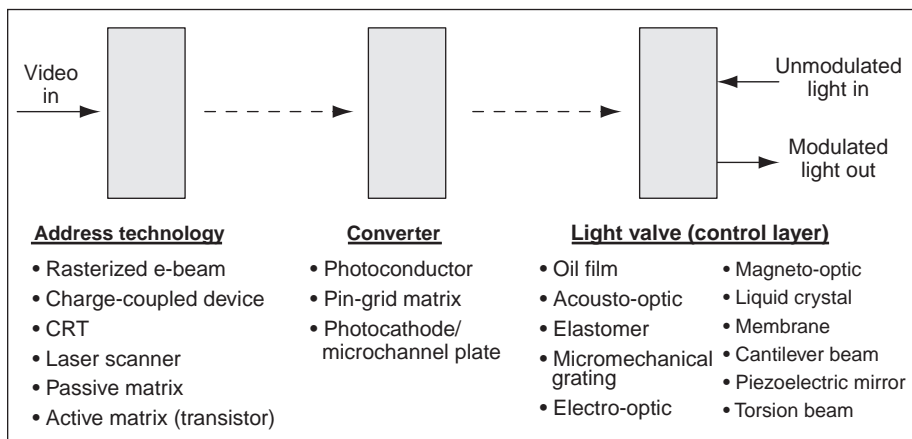


**Figure 11.** The light-valve technology matrix.

The figure shows a block diagram with Video in → Address technology → (dashed arrow) → Converter → (dashed arrow) → Light valve (control layer), with Unmodulated light in and Modulated light out.

**Address technology**
- Rasterized e-beam
- Charge-coupled device
- CRT
- Laser scanner
- Passive matrix
- Active matrix (transistor)

**Converter**
- Photoconductor
- Pin-grid matrix
- Photocathode/ microchannel plate

**Light valve (control layer)**
- Oil film
- Acousto-optic
- Elastomer
- Micromechanical grating
- Electro-optic
- Magneto-optic
- Liquid crystal
- Membrane
- Cantilever beam
- Piezoelectric mirror
- Torsion beam

| Light valve (control layer) | Light modulating method | | | |
|---|---|---|---|---|
| | Scattering | Diffraction | Polarization | Beam steering or defocus |
| • Oil film | | X | | |
| • Acousto-optic | | X | | |
| • Elastomer | | X | | |
| • Micromechanical grating | | X | | |
| • Electro-optic | | | X | |
| • Magneto-optic | | | X | |
| • Liquid crystal | X | X | X | |
| • Membrane | | | | X |
| • Cantilever beam | | | | X |
| • Piezoelectric mirror | | | | X |
| • Torsion beam | | | | X |

**Figure 12.** Light-modulation properties of control layers.
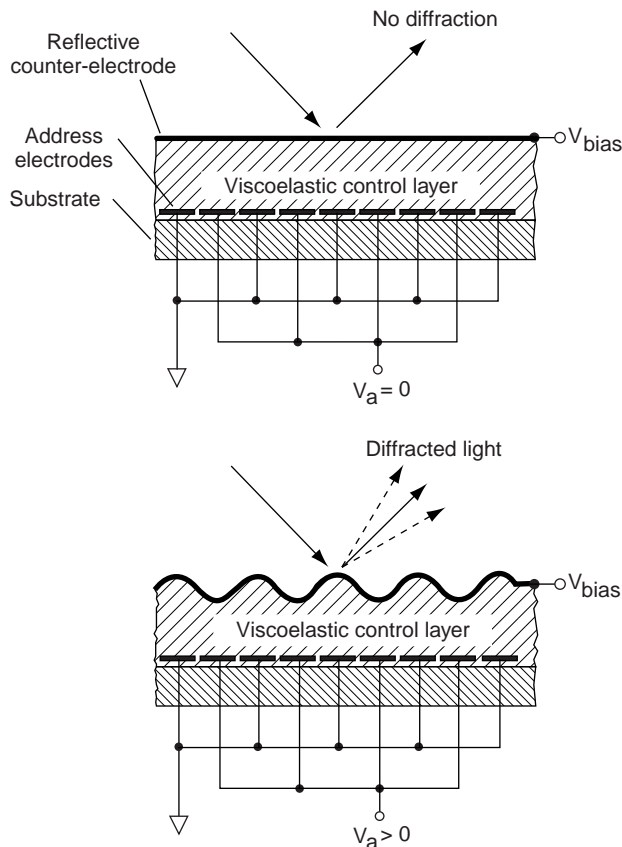


**Figure 13.** Electrode-addressed elastomer light valve.[25]

electrostatic force developed between the energized address electrodes and counter-electrode. Because the elastomer is incompressible, it protrudes into the spaces between the energized electrodes. The result is a diffraction grating effect for the energized pixel. The elastomer surface of the non-energized pixel remains flat. The thickness of the elastomer layer and the spatial frequency of the address electrodes are chosen to maximize the response of the elastomer to the applied voltage.

The optics of the elastomer light valve are similar to the Eidophor optical system. The diffraction grating of the energized pixel causes light to be diffracted around the optical stop of the Schlieren projection optics. Thus the energized pixel appears bright at the projection screen. The non-energized pixel appears dark. Gray scale is achieved by varying the voltage on the address electrodes.

The address voltage is periodically shifted at the video frame rate between pairs of electrodes so that the regions of compression are not always at the same location. This technique avoids a gradual imprint of the surface that would lead to a residual image effect at the projection screen.

Although work on elastomer light valves has been carried out for more than 30 years, the possibility of producing a commercially viable projection display with this technology has been elusive.

## Micromechanical grating light valve

The micromechanical grating light valve, first described in 1992, is another technology that modulates light by diffraction, but unlike other diffraction-based technologies, it is digital.[30] The commercial name for this technology is Grating Light Valve™ (GLV™). *Figure 14* shows a cross section of one GLV pixel for an energized and non-energized state.[31] Electrostatically deflectable microbridges are made from silicon nitride that is deposited in tension over a silicon dioxide sacrificial spacer. The bridges are overcoated with aluminum for reflectivity. The air gaps are formed by using an isotropic wet etch to selectively remove the sacrificial spacer.

The GLV is passive-matrix addressed by a set of row and column electrodes. Every other microbridge in the pixel is addressable. The others are held at a fixed bias voltage so that they cannot be energized by the column address electrodes of the passive matrix. When a pixel is selected by the combined effect of the row and column address voltages, the air gap voltage of the selected microbridges exceeds a threshold level. The movable bridges deflect through one-quarter the wavelength of the incident light and touch



**Figure 14.** Grating Light Valve™(one pixel).[31]

down onto the substrate. They remain there, electro-mechanically latched, as long as a minimum holding voltage is maintained by the row electrode.

Light, which is reflected from an energized pixel, is strongly diffracted because the optical path difference upon reflection between pairs of microbridges is one-half of a wavelength (destructive interference condition at that wavelength). For the non-energized state, the microbridges are coplanar and the light is specularly reflected. A Schlieren optical system is used to block the specularly reflected light and to image the diffracted light. The optical states are digital and therefore gray scale is produced by using pulsewidth modulation.

Because the inertia of the microbridges is small and they only need to move over small distances, the switching speed from one mechanical or optical state to the other is on the order of 20 nanoseconds. With this high switching speed and the latching property of the microbridges, it is not necessary to use active-matrix addressing. GLV technology has recently been demonstrated using a one-dimensional array of GLV pixels in conjunction with a white-light laser source and a polygon scanner.[32]
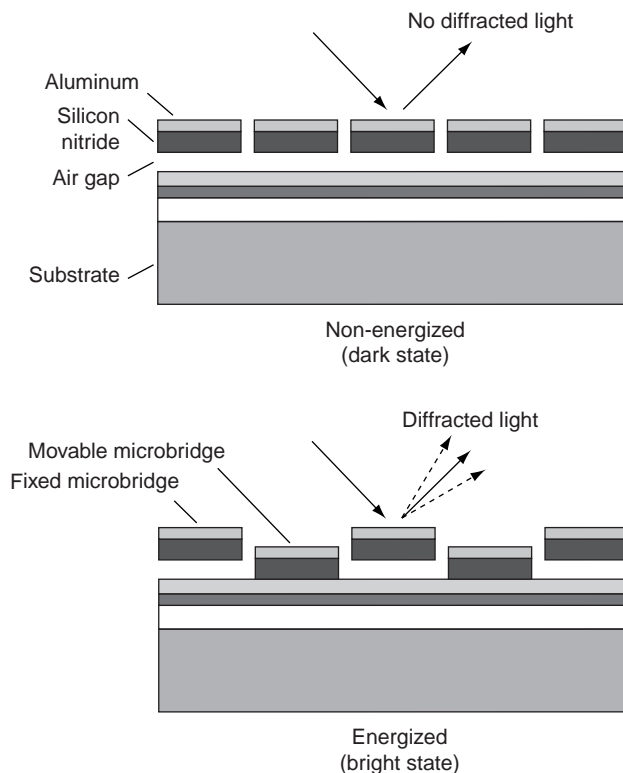
## Electro-optic light valves

Electro-optic light valves were proposed in the 1930s using zinc selenide (ZnSe), but it was not a practical display material because of its low electro-optic sensitivity and the difficulty of growing sufficiently large crystals. In the 1970s the availability of ferroelectric materials belonging to the family of potassium-dihydrogen-phosphate (KDP) compounds solved these problems. Large crystals could be grown, and large electro-optic sensitivities could be obtained by operation just above the Curie temperature of the crystal, at which the crystal is monostable and analog operation is possible. Below the Curie temperature the crystal is bistable, and in this temperature regime it can be used for storage displays.

In the early 1970s several KDP-based light-valve projection displays were demonstrated, either e-beam addressed or light-addressed using a photoconductor/KDP sandwich structure.[33,34] Operation of these displays is based on the Pockels effect. (As we shall see later, certain types of liquid crystal displays use the same effect to modulate light.) A voltage (V) is placed across the faces of the crystal as shown in *Figure 15*, which in turn induces an electric field within the crystal. At zero applied voltage, the refractive index in the plane of the crystal face is independent
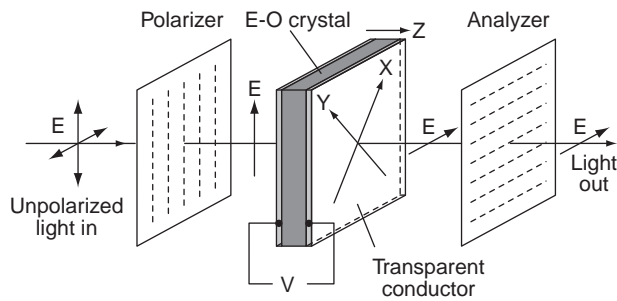
**Figure 15.** Ferroelectric light valve (shown for condition of maximum transmission).

of direction. But with applied voltage, the field causes the refractive index to vary with direction and the crystal is said to be "birefringent." The variation in refractive index with direction is proportional to the applied field.

To make use of the Pockels effect for light modulation, the crystal is placed between a polarizer and a "crossed" analyzer. The polarizer passes plane-polarized light to the crystal face. At zero voltage the plane-polarized light passes through the crystal undisturbed and is blocked by the analyzer. This is the off state for the light valve. As the crystal becomes more birefringent with applied voltage, the light becomes more elliptically polarized. The light output increases because its electric field (E) has an increasing component that is parallel to the analyzer. The condition of maximum brightness (shown in Figure 15) occurs when the light has become plane-polarized again, but rotated at 90 degrees relative to the input light.

Electro-optic light valves using single-crystal materials have a number of limitations. These include high-voltage addressing, nonuniformities caused by imperfections in the crystal and the requirement for cooling below room temperature to maximize sensitivity.

Another class of ferroelectric materials, lanthanum-modified lead zirconate-titanate (PLZT) ceramics, has also been developed. These show good electro-optic sensitivity at room temperature, can be driven at lower voltages and are easier to fabricate than single-crystal ferroelectric materials.[35] PLZT relies for its operation on the Kerr electro-optic effect that is similar to the Pockels effect, except that the applied electric field is transverse rather than parallel to the direction of optical propagation.

PLZT-based projection display architectures and fabrication techniques have been proposed and test

devices have been characterized.[36,37] To date such displays have not proven practical.

## Magneto-optic light valves

Magneto-optic light valves use the Faraday effect to digitally modulate light by rotating the polarization direction as light passes through the transparent magnetic material. The light valve is placed between crossed polarizers in the same optical arrangement used for electro-optic light valves. This digital technology was developed in the 1980s for optical signal processing and potential projection display applications.[38,39]

The light valve is formed from a transparent magnetic iron-garnet film supported on a non-magnetic transparent substrate. The magnetic film is etched into a two-dimensional array of mesas. The mesas are addressed by a passive matrix consisting of a two-dimensional array of conductors, as shown in *Figure 16*. At the cross point of two conductors that are both carrying current, a sufficient magnetic field is developed to locally switch a corner of the mesa from one magnetization direction to the other. An external magnetic field is then applied to complete the switching action, driving the magnetic domain wall across the entire mesa. Because this technology is inherently digital, gray scale would be produced by using pulsewidth modulation.

Although the application of this technology has been proposed for pulsewidth modulation projection displays, the magneto-optic light valve is probably
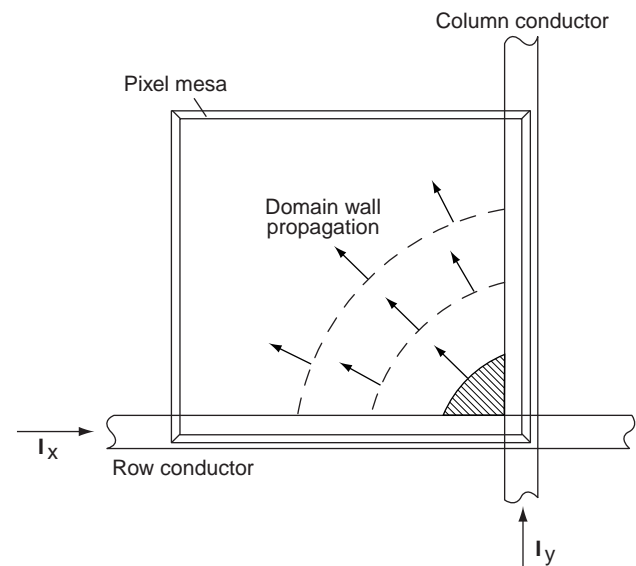


**Figure 16.** Switching principle of the magneto-optic light valve.

not a good candidate. In large array sizes it is subject to excessive heating caused by the current flowing in the passive matrix conductors. Furthermore, because of the lack of integrated current drivers for the row and column conductors, packaging would be prohibitively expensive.

## Liquid-crystal light valves

Only a few years after the discovery of cathode rays, an Austrian botanist, Friedreich Reinetzer, correctly concluded in 1888 that there existed an intermediate phase between solid and liquid in a cholesterol-related material that he was studying. Two melting points were observed. One where the solid melted into a milky looking liquid, and a second melting point at a higher temperature at which the cloudy liquid turned into a clear liquid. The intermediate liquid phase that appeared cloudy was later named the liquid-crystal phase.

It took a mere 21 years from the discovery of cathode rays to their first display implementation. In contrast, nearly 80 years passed between the discovery of the liquid-crystal phase and its implementation as a liquid crystal display. In the 1920s and 1930s there was much research on the electro-optic properties of liquid-crystal materials. This work led to what is probably the first patent on a single-element light valve that used liquid crystals. It was awarded to the Marconi Wireless Telegraph Company in 1936.[40] Its application was for "electro-optical translating systems," and its stated advantage was as a low-voltage and more sensitive replacement for electro-optic materials such as the liquid nitrobenzene.

It wasn't until the pioneering work at RCA Laboratories of George Heilmeier and a team of his associates that the ideas were put together for the first liquid crystal displays. During the period 1964 to 1968 they discovered many of the effects that would later be commercialized, including dynamic scattering, dichroic dye (guest-host) LCDs and phase-change displays. Until that time there were no known materials that had a liquid-crystal phase at room temperature. (The Marconi patent describes a heater for keeping the material in its liquid-crystal state.) Heilmeier's team discovered that by mixing pure liquid-crystal materials together, they could produce liquid-crystal solutions that would operate over a broad temperature range, including room temperature.

Several excellent reviews have been written on the subject of LCD technology and its history.[41-45]

*Liquid-crystal state*—But what is the liquid-crystal state? An example of a "nematic" liquid crystal is shown in *Figure 17*. Its phases are shown as a function of increasing temperature. The organic molecules are long, planar rod-like structures. In the solid state, the molecules of a liquid crystal are rigidly aligned in a repetitive pattern. They behave as any other crystalline material. As the temperature is increased, the material melts into an intermediate or liquid-crystal phase. Here the molecules are free to move but are constrained to having their long axes pointed in generally the same direction. Nematic is from the Greek word for "thread" because in the liquid-crystal phase, this material appears thread-like when viewed under a microscope. Finally, as the temperature is further increased, the material melts into an isotropic liquid state, in which the molecules are randomly oriented and free to move around. A nonliquid-crystal material melts directly from the crystalline solid state into the isotropic liquid state.
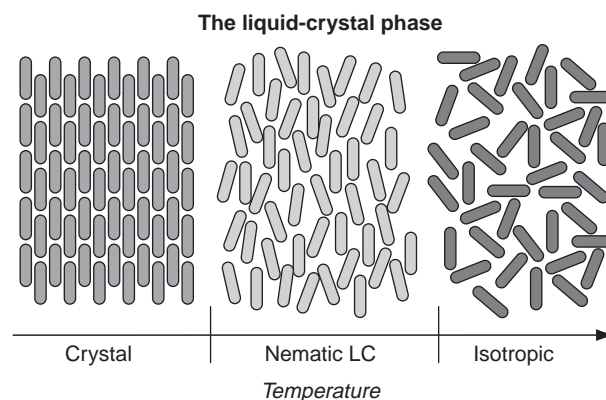
**The liquid-crystal phase**



**Figure 17.** The phases of a nematic liquid crystal as a function of temperature.[46]

The liquid-crystal phase can have other types of spatial ordering besides nematic, as shown in *Figure 18.* "Smectic" liquid crystals (from the Greek word for "soap") are aligned with their long axes generally in the same direction, and are arranged in layers as well. "Cholesteric" liquid crystals are similar to smectic liquid crystals, except the direction of alignment in each layer slowly changes from layer to layer to form a helical structure. The name cholesteric was given to this class of liquid crystals because they were originally associated with cholesterol. Perhaps it is more appropriate to call them chiral nematic.

The property that makes liquid crystals useful for displays is their highly anisotropic dielectric constant. Because the molecules are in the liquid state and
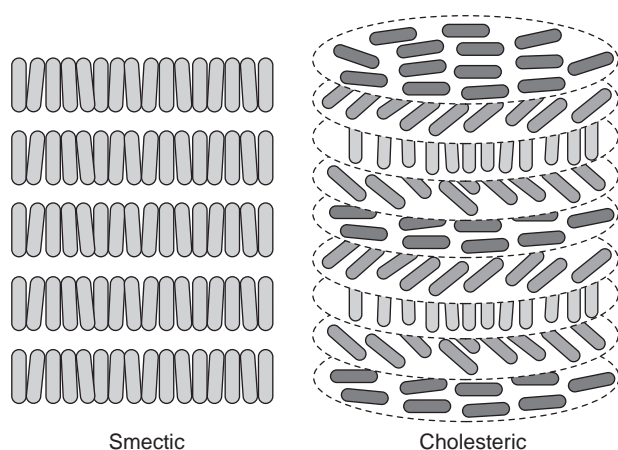
**Figure 18.** Smectic and chiral nematic (cholesteric) liquid crystals.[46]

have dielectric anisotropy, they can be oriented by an externally applied electric field (E), much as metal filings can be oriented in a magnetic field. If the dielectric constant ($\varepsilon$) is larger along the long axis (or director) of the molecule compared to the short axis, the liquid crystal is said to have positive dielectric anisotropy. For this class of materials the long axis of the molecule tends to align parallel to an applied electric field as shown in *Figure 19.* For materials in which the dielectric constant is smaller along the long axis compared to the short axis, the dielectric anisotropy is negative and the molecule tends to align with its long axis orthogonal to the field.
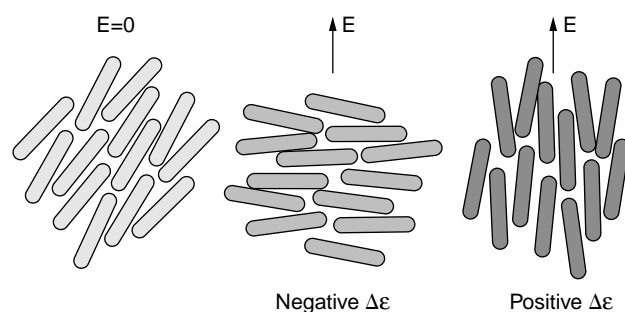


**Figure 19.** Effect of electric field on orientation of nematic liquid crystals.

***Guest-host and dynamic scattering***—Heilmeier's original interest was in nematic liquid crystals that were altered with the addition of a special dye consisting of long molecules that tended to align parallel to the long molecules of the liquid crystal.[47] He formed a cell by placing the mixture between two glass plates that were coated with transparent conducting layers of tin oxide for address electrodes.

When a voltage was applied to the electrodes of the cell, the liquid crystal molecules were reoriented by the electric field and the dye molecules were carried along. He demonstrated what is now called the guest-host liquid-crystal effect. To make the effect visible, the cell was illuminated with polarized light. Depending on whether the polarization direction was parallel or perpendicular to the long axis of the dye molecules, the light was absorbed or not absorbed by the dye and the color of incident white light could be modulated.

During their investigations, Heilmeier and his co-workers discovered the "dynamic scattering" effect.[48-49] In certain nematic materials, as the voltage was increased, the applied field produced turbulence rather than molecular reorientation and light was scattered by the variations in the index of refraction. They discovered that charge impurities in the material were accelerated in the electric field, creating a breakup of the material into domains having randomly directed axes.

When the pixel was activated, it appeared milky white. By replacing one of the transparent electrodes with a reflective conducting material, the liquid-crystal cell could be made reflective and used with ordinary room light without polarizers. Although contrast was low, the dynamic scattering LCD found immediate application in early wristwatch and portable calculator displays. It was clearly visible with conventional overhead lighting. It had low power consumption compared to the existing technology, light-emitting diode displays. The announcement of the dynamic scattering effect was made by RCA in 1968, generating lots of excitement in the display community.

That same year a direct view, reflective dynamic scattering display was demonstrated using e-beam addressing and a pin-grid matrix converter.[50] Both stationary and live television programming were displayed in this first-of-a-kind demonstration of LCD technology.

***Transmissive, twisted nematic LCDs***—In 1969 another major breakthrough in liquid-crystal development was made, with the invention of the twisted-nematic (TN) field effect alignment mode for display applications.[51] Much controversy has ensued over the years regarding the rightful inventor(s), James L. Fergason or Wolfgang Helfrich and Martin Schadt.[52] Even litigation has not settled this issue in the minds of many.

TN technology soon displaced dynamic scattering LCDs because of its inherently higher contrast and higher long-term reliability. The TN-LCD shown in *Figure 20* is the most commonly used LCD mode for transmissive projection display light valves.

As in the Heilmeier guest-host dye and dynamic scattering cells, the liquid crystal is contained between two glass plates coated with transparent conducting layers for the address electrodes. To make the twisted nematic alignment mode work, the liquid-crystal molecules at the surface of each plate must align with a particular direction in the plane of the plate. To ensure this alignment, a polymer is deposited on both electrodes and rubbed along the desired alignment direction to produce microgrooves in the surface. The long axes of the liquid-crystal molecules that are in contact with the alignment layer tend to line up with the rubbing direction. The glass plates are oriented with their alignment direction at 90 degrees with respect to one another so that the molecules are twisted by 90 degrees in going from one electrode to the other. A polarizer is oriented so that plane- (linearly) polarized light enters the twisted nematic cell with its polarization direction parallel to the alignment direction of the entrance plate.

In the absence of an applied field, the electric vector of the polarized light follows the twist of the liq-uid-crystal molecules and exits at 90 degrees relative to its original direction. If an exit polarizer (analyzer) is oriented at 90 degrees relative to the entrance polarizer, the light is undisturbed and transmitted through the exit polarizer. (The polarization direction follows the twist because of the high dielectric constant along the long axis of the molecules. This is sometimes called "wave-guiding").

On the other hand, if a sufficiently large electric field is applied, the molecules are disrupted from their 90-degree twist, and because they have positive dielectric anisotropy, the long axes of the molecules align parallel to the electric field (E). The polarization direction is no longer rotated and the light is blocked at the exit polarizer. Intermediate levels of light transmission (for gray scale) are achieved by using lower voltages so as not to completely remove the 90-degree twist.

***Reflective LCDs***—A reflective LCD light valve is created when one of the transparent electrodes is replaced with a reflective electrode. Reflective LCDs require special alignment modes. The 90-degree twisted nematic mode is not used for reflective applications because of its inability to fully modulate the light, which results in reduced brightness.[53] Two alignment modes have found widespread use for
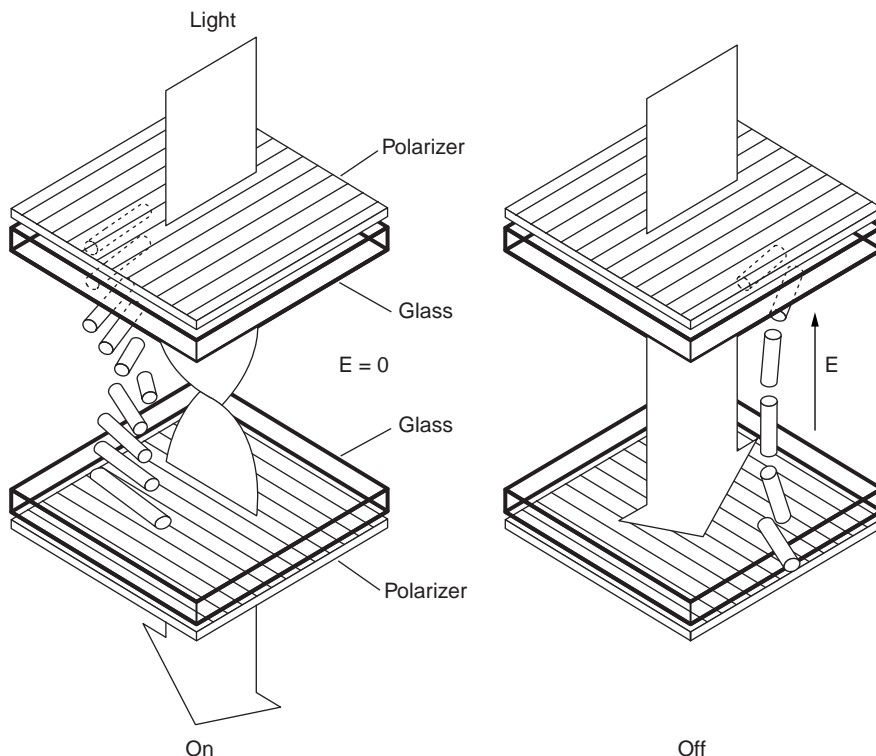


**Figure 20.** The twisted nematic LCD.[44]

reflective applications, the 45-degree twisted nematic and the homeotropic mode.

The homeotropic alignment mode is illustrated in *Figure 21.*[54] Over the years it has also been called tilted perpendicular alignment (TPA), deformation of aligned phase (DAP) or electric-field controlled birefringence (ECB). In the absence of an applied electric field, nematic liquid crystal molecules are aligned with their long axes nearly perpendicular to the address electrodes. An alignment layer processed on the surface of the electrodes is engineered to give the molecules a small initial pretilt angle, important in preventing disinclination of the molecules near pixel electrode edges. In this near-vertical alignment, the index of refraction is independent of direction for incident light normal to the surface.
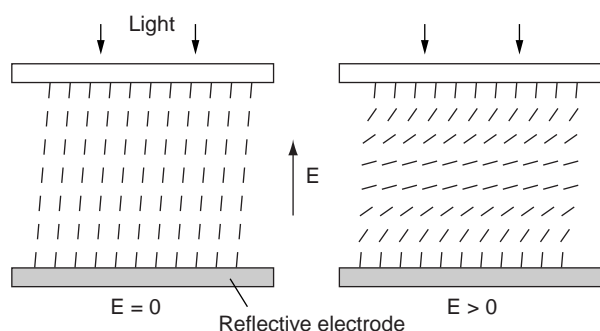


**Figure 21.** The homeotropic alignment mode.

A nematic liquid crystal with a negative dielectric anisotropy is chosen so that, as the electric field increases, the long axes of the molecules rotate in the direction orthogonal to the field. The molecular reorientation results in an index of refraction that is no longer independent of direction (the liquid crystal is now birefringent). The variation in refractive index with direction is a function of the applied field.

To make use of the homeotropic or other alignment modes in a reflective configuration, a polarizing beam splitter is required, as shown in *Figure 22.* Unpolarized light enters the beam splitter and plane-polarized light (s-wave component) is reflected into the liquid-crystal cell. In the case of homeotropic alignment, with no applied voltage to the cell, the index of refraction is independent of direction and therefore the s-wave is undisturbed. It is reflected at the polarizing beam splitter and back into the light source. This is the dark state, as no light reaches the projection lens.

A voltage applied to the cell causes the liquid crystal to become birefringent and the plane-polarized
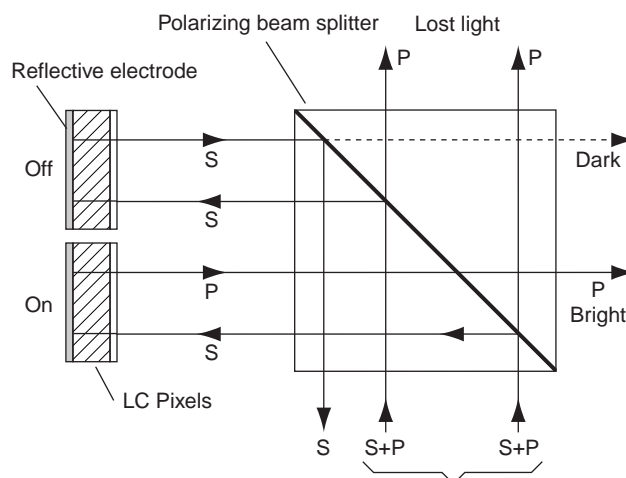


**Figure 22.** Reflective LCD light modulation (shown for condition of maximum brightness).

s-wave becomes elliptically polarized. In this condition, the light has both s-wave and p-wave components. The p-wave (90-degree rotated s-wave) is able to pass unreflected through the polarizing beam splitter and into the projection lens. As the applied voltage increases, the amplitude of the p-wave increases and that of the s-wave diminishes until all of the light is p-wave. This is the condition of maximum brightness.

Another alignment mode used for reflective LCDs is the 45-degree twisted nematic mode, also known as the hybrid field effect mode. It employs a 45-degree twist for the off state and an untwisted, birefringent state for the on state.[53] Other twist angles have been employed that are optimized for the polarizer orientation and birefringence-thickness product of the liquid crystal.

***The photoactivated liquid-crystal light valve***—One of the earliest and most successful LCD projectors is the photoactivated liquid-crystal light valve (LCLV). Developed by Hughes Research Laboratories, this reflective LCD technology was first reported in 1973. It used a CRT-addressed photoconductor to modulate the voltage across a dynamic scattering liquid crystal.[55]

In 1975 the display contrast was improved by replacing the dynamic scattering liquid crystal with a homeotropic mode, nematic liquid crystal.[56] But because the near-vertical alignment of the liquid-crystal molecules was not photostable, the homeotropic mode was used for only a short time. In 1977 it was replaced with the 45-degree twist, hybrid field effect mode.[57,58] Finally in 1990, a homeotropic

alignment mode process was developed with improved photostability and with higher contrast ratio than was possible for the 45-degree twist mode.[59]

The photoactivated LCLV is currently known as the Hughes-JVC Image Light Amplifier™ (ILA™). It has provided an alternative to the oil-film projectors for high-brightness, color projection display applications and is similar to the oil-film technology in two respects. Both the liquid crystal and the oil-film layer are continuous, non-pixelated surfaces. Through the use of a light-to-voltage converter, the photoactivated LCLV is addressed by the light output from a CRT. Therefore, the source of addressing for both the photoactivated LCLV and the oil-film technology is a rasterized e-beam.

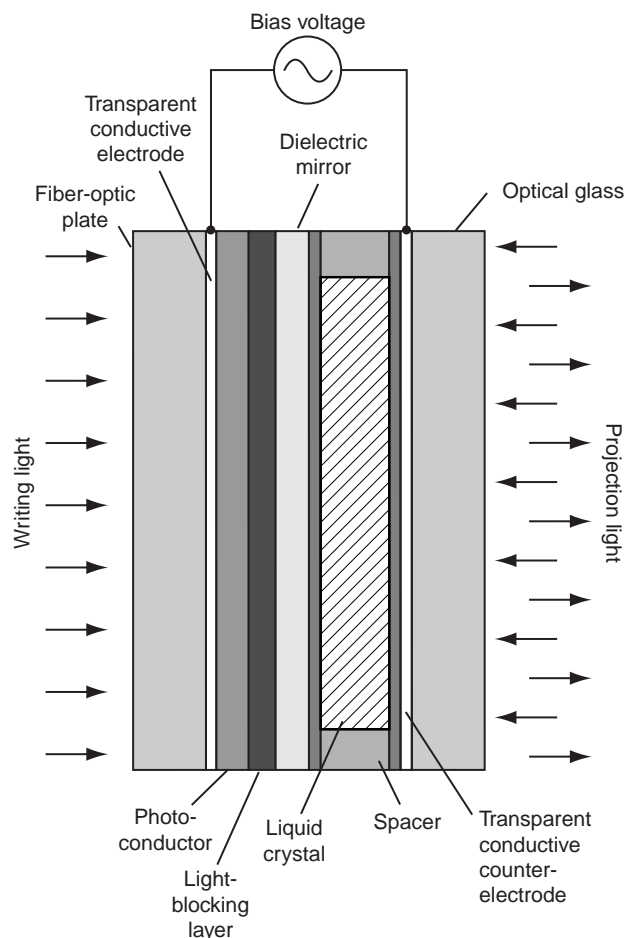A cross section of the photoactivated LCLV is shown in *Figure 23*. A photoconductor film and a homeotropically aligned nematic liquid crystal are separated by a light-blocking layer and dielectric mirror. The photoconductor acts as a light-controlled voltage modulator for the liquid crystal. The dielectric mirror reflects the projection light and the light-blocking layer rejects residual projection light from entering the photoconductor.

An ac bias voltage is applied across the transparent electrodes. When there is no light on the photoconductor, it has a high resistivity and there is only a small amount of ac voltage drop across the liquid crystal. Most of the drop is across the photoconductor. But when part of the photoconductor is illuminated, its resistivity is reduced in proportion to the intensity of the light, and the ac voltage drop across the liquid crystal in the vicinity of the illumination is increased.

A simplified schematic of a simple monochrome projection system is shown in *Figure 24*. A description of the optical operation of the homeotropic alignment mode and polarizing beam splitter were presented earlier in this section. An advantage of the photoactivated LCLV is the fact that its resolution is not fixed by a built-in pixel structure. Therefore, systems can be designed with addressing provided by extremely high-resolution CRTs or laser scanners for high-information-content display applications.[60,61]



**Figure 23.** Photoactivated liquid-crystal light valve.[59]
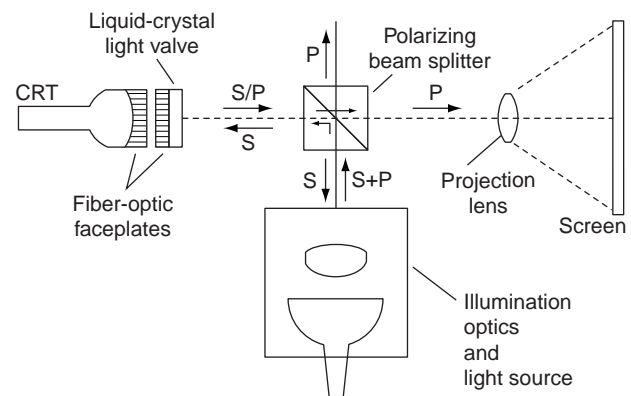


**Figure 24.** Monochrome photoactivated LCLV projector.[62]

***Pixelated light valves***—The oil-film and the photoactivated liquid-crystal light valves are examples of non-pixelated structures. Their addressable resolution is determined by the number of e-beam lines. On the other hand, there are light valves for which the addressable resolution is fixed by dividing the display area into pixels and addressing with an x-y matrix of row and column electrodes.

There are several advantages to a pixelated light-valve approach. In a color projection system, three light valves are generally used, one for each primary color (R,G,B). In a non-pixelated light-valve projector, the electron beams from three electron guns are aligned to converge the primary color images at the projection screen. This can require initial adjustment and maintenance of the registration. On the other hand, in a pixelated light-valve projector, convergence is set at the factory and no further adjustments are normally required. Another advantage of pixelated structures is that they can be addressed with an active matrix of transistors. This provides for a more compact and lower weight projection display system compared to e-beam or CRT-addressed systems requiring glass vacuum bottles.

*Passive-matrix addressing*—The earliest and simplest approach to addressing a matrix of liquid-crystal pixels is called passive matrix addressing. It consists of an x-y matrix of row and column electrodes, as shown in *Figure 25*. The intersection of each row and column electrode defines one pixel. The bottom address electrode is connected to a row electrode, the top to a column electrode. The object of the passive-matrix addressing scheme is to generate a set of voltage waveforms on the row and column electrodes so that any set of intersections can be activated without turning on unselected intersections. There are two properties of the liquid crystal that make this scheme work, provided the matrix is not too large. First, there is a threshold voltage below which the liquid-crystal cell is not turned on. Second, the liquid crystal responds to the square of the applied voltage, averaged over a time shorter than the turn-on time for molecular reorientation.The sharper the threshold for turning on the liquid crystal, the larger the number of rows and columns that can be successfully addressed with the passive- matrix technique. Over the years, research has led to display architectures called
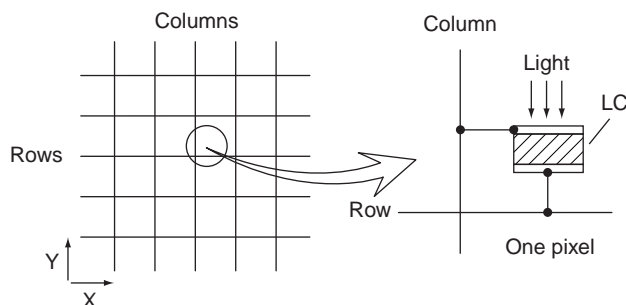


**Figure 25.** Passive-matrix address method.

"supertwisted nematic," or STN, which have provided sharper thresholds and the ability to address more lines.

*Active-matrix addressing*—As the number of resolution lines increases, passive-matrix addressing begins to fail. Pixels that are supposed to be off turn on, and the contrast ratio is degraded. Active-matrix addressing solves this problem. As shown in *Figure 26*, at the intersection of each row and column electrode, a single transistor acts as an analog switch. One side of the transistor is connected to the column electrode and the other side to both a "storage" capacitor ($C_s$) and to a liquid-crystal capacitor ($C_{LC}$). The liquid-crystal capacitor is formed by the sandwich structure consisting of the address electrode, the liquid-crystal material and a grounded counterelectrode.
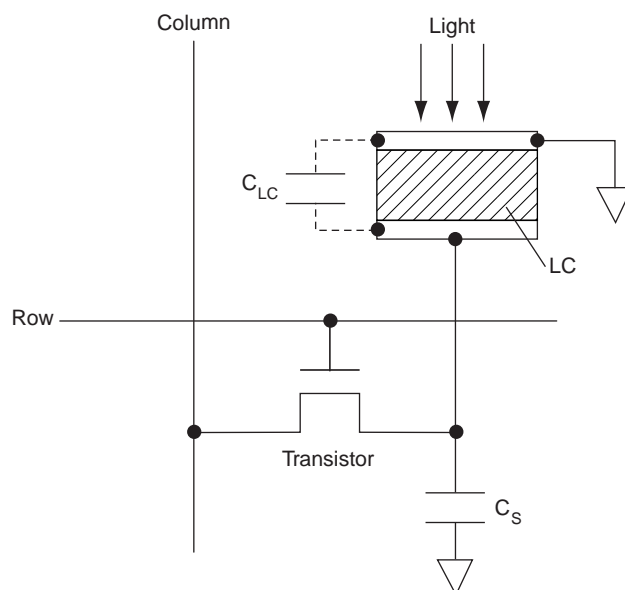


**Figure 26.** Active-matrix circuit for LCD.

The addressing circuit works in the following way. First, the column electrodes are charged to the desired analog voltage levels for a given line. Then the transistor switches for that line are turned on by the row electrode and the capacitors are charged to the analog voltage levels set on the column electrodes. After the switches in that row are turned off, those voltages remain stored until the next video frame, when the capacitors are recharged or refreshed to new analog voltage levels.

Light leakage from the projection lamp can produce photogenerated leakage currents in the transistors. Leakage currents are also produced by the finite

off impedance of the transistor. The storage capacitor $C_s$ adds capacitance to reduce the discharge effect on the stored voltage.

Early LCD panels were transmissive and fabricated on large glass substrates. The transistors developed for use on the glass substrates are called thin-film transistors or TFTs. They differ from bulk silicon transistors in that the active channel of the transistor is fabricated from a thin-film deposition, whereas bulk silicon transistors (memories, microprocessors, etc.) are formed from single-crystal silicon. The TFT concept using cadmium selenide (CdSe) as the active material was demonstrated and reported in 1962 by P.K. Weimer of RCA.[63]

T.P. Brody and others working at Westinghouse Research Laboratories reported the first use of active-matrix addressing for an LCD display in 1973.[64] At first they focused on tellurium and later they switched to CdSe as the semiconducting material. In 1979 P.G. Le Comber reported the operation of TFTs formed from amorphous silicon.[65] This material was compatible with glass substrates because it had a low deposition temperature (~300 °C) and the technology for depositing amorphous silicon over large areas could be borrowed from solar cell technology. Le Comber's report led to a surge in the development of active-matrix addressing for LCDs.

A cross section of an amorphous silicon TFT is shown in *Figure 27*. The architecture has an inverted gate structure in which the gate of the transistor is under the semiconducting material, as opposed to the usual arrangement of gate on top for single-crystal silicon transistors.
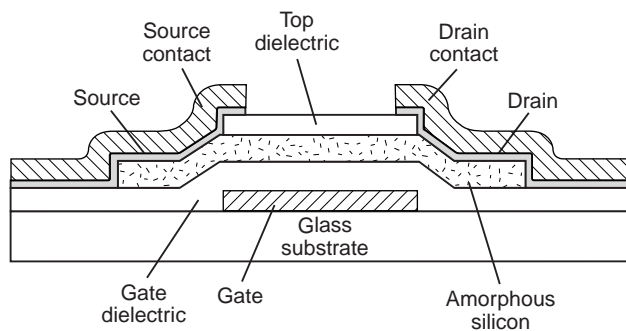


**Figure 27.** Inverted gate, amorphous silicon TFT.

The ideal TFT switch combines a low on resistance with a high off resistance. Amorphous silicon is much inferior to its single-crystal counterpart in these respects, and oversized TFT transistors are required

to compensate for these deficiencies. In a transmissive LCD light valve, larger transistors mean less clear aperture for the light to pass through, because the transistors require an opaque light shield placed over them. Light leakage into the transistor produces photogenerated charge that will discharge the capacitor.

Following the commercialization of amorphous silicon LCD panels, there has been a large effort to produce TFT materials having more ideal transistor properties. This effort has been driven by the need to maximize the clear aperture, increase the display resolution, reduce the size of the LCD panel and its associated optics and to integrate row and column drivers on the same glass substrate. The result has been the polysilicon transistor that in recent years has become the main approach for LCD light valves. Panel sizes for projection display applications have been reduced from 6 inches on a side to diagonals of 1.3 inches or less while maintaining high aperture ratios.[66]

However, the quartz substrates used in the preparation of polysilicon transistors are expensive. Recently, a lower temperature polysilicon (low-temp poly) approach has been developed in which glass can be used instead of quartz for the substrate. In this process amorphous silicon is deposited onto glass substrates and recrystallized by locally heating the amorphous silicon with an excimer laser.

***LCD projectors, a decade of rapid progress***—The first LCD color video projector was introduced to the market in 1989 by the Sharp Corporation. Although of limited resolution, its introduction signaled a decade of rapid developments leading to video and graphic projectors with higher resolution, greater light efficiency and brightness, improved colors and reduced weight and volume.

Early LCD projectors employed transmissive cells based on amorphous silicon TFTs or diode switches. The weight and volume of these projectors were reduced by continuing efforts to shrink the size of the pixels and the resultant size of the LCD panel and associated optics. To maintain a high aperture ratio for efficient light transmission, the large amorphous silicon transistors of the earlier panels were replaced with more compact polysilicon transistors. Today, compact projectors typically employ polysilicon-addressed LCD panels, ranging in size from 0.9 to 1.3 inches on the diagonal and based on the 90-degree twisted nematic alignment mode.

*Figure 28* shows an example of a compact transmissive LCD projector.[67] This particular design addresses the classic problem of polarization losses that amount to more than 50% of the available light from the lamp. It employs a polarization recovery system to deliver exceptional luminous efficiency.

Light from the arc lamp passes through a microlens integrator that homogenizes the light beam for improved uniformity. The polarization recovery plate polarizes the light and then acts on the rejected polarization component by rotating its polarization direction and reinserting it into the optical path. The white light (W) is then separated into its primary colors, red, green and blue (R,G and B) by a series of dichroic filters and directed to three LCD panels, one for each color. After the light is modulated, a color-combining dichroic "x-cube" combines the red, green and blue images into a single color image that is projected to the screen.

In addition to polarization recovery, another technique can be used for increasing the luminous efficiency. A microlens array focuses light from the condenser lens into the clear aperture of each pixel, thus increasing the apparent aperture ratio. Taken together, these two enhancements to the luminous efficiency have overcome the classic problem of low luminous efficiency in polarization-dependent, transmissive LCD projectors.

Driven by the need for higher resolution projectors that are both compact, lightweight, and efficient, a new class of projector products has been announced in 1998. These products use reflective LCD light valves on single-crystal silicon address circuits (so-called silicon backplanes). They employ even smaller pixels, because the address circuitry can be hidden under the reflective aluminum address electrode of the pixel (similar to the DMD architecture described later). Both homeotropic[68-70] and 45-degree twisted nematic[71,72] liquid-crystal alignment modes are employed.

The optical layout of the reflective LCD projector is similar to the transmissive projector, except polarizing beam splitters are used to reflect the light into each LCD chip. The polarizing beam splitter was introduced earlier and illustrated in Figure 22.

***Other LCD projection technologies—***There are a number of other LCD technologies that have potential application for projection display applications. One of these is the ferroelectric liquid crystal (FLC) display, a bistable light valve that can be used in the reflective mode over a single-crystal silicon address circuit.[73] The FLC material consists of LC molecules that have a permanent electric dipole moment.

Application of a voltage pulse with polarity in one direction or the other causes the FLC to switch between two stable molecular orientational states.[74]
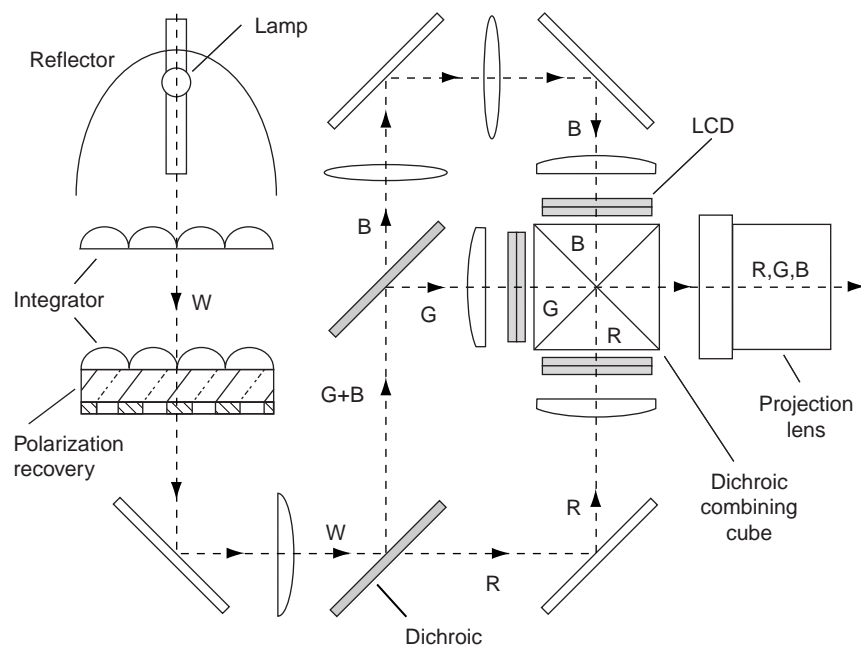


**Figure 28.** Transmissive LCD projector. [67]

As the FLC is switched from one state to the other, polarized light is modulated between bright and dark states. Because light can only be turned on or off, gray scale is achieved by a pulsewidth modulation technique.

The switching speed of the FLC with 5-volt address is short compared to normal nematics (~100 μs vs. ~10 ms). The shorter switching speed results from the strong forces exerted on the molecules by the electric field because of their permanent electric dipole moment. In a time-multiplexed color application using a single FLC device and a rotating color disc, this switching speed will support 64 gray levels per primary color.

Two other LCD technologies are of note because they do not require polarized light and thus do not have the light losses associated with polarizers. The first is often called polymer-dispersed liquid crystal (PDLC), although it has a variety of other names.[75,76] The transmissive version is shown in *Figure 29*.
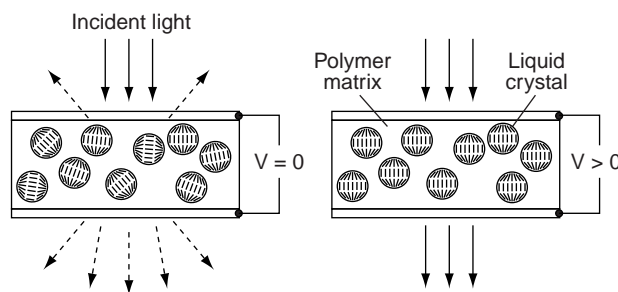


Figure 29. Polymer-dispersed liquid crystal.[75]

The PDLC material consists of droplets of a nematic LC dispersed in a solid polymer matrix. With no applied electric field, each droplet of LC is randomly oriented, producing a random change in index of refraction. Light passing through the cell is scattered, leading to a dark off state. When a field is applied, the LC molecules within each droplet align with the field, producing a near uniform index of refraction. Light is no longer scattered, resulting in a bright cell.

A second LC technology that does not require a polarizer relies on light diffraction, working on the same principle as the oil film, acousto-optic, elastomer and micromechanical grating light valves.[77] *Figure 30* illustrates one technique for producing a diffraction grating LCD.[78] Within each pixel a set of fine transparent electrodes is patterned as shown. With zero applied electric field, all LC molecules are
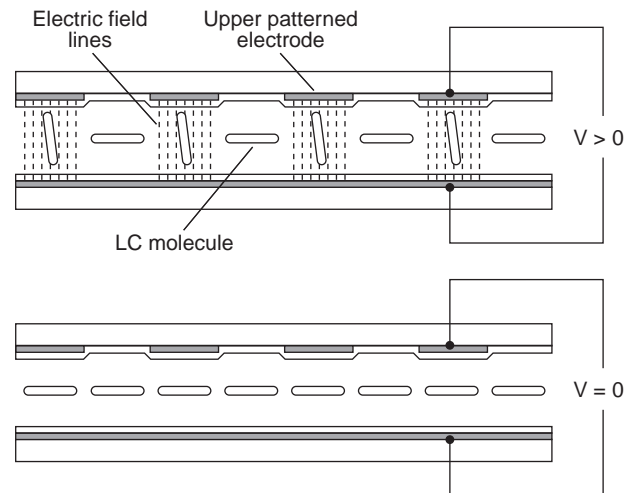


**Figure 30.** Diffraction grating LCD (one pixel).[78]

oriented in the same direction. With an applied field, the molecules rotate under each electrode and a diffraction grating is produced by the periodic variations in index of refraction.

Projectors based on PDLC or diffraction-grating LC technology have lower image contrast than projectors based on polarization modulation. The recent introduction of practical polarization recovery optics and microlens illuminator arrays has mitigated the luminous efficiency advantage of these technologies and made them less attractive for projection applications.

*LCD performance issues*—There has been a continuing effort over the years to improve the performance characteristics of the LCD, including molecular response times (image lag), contrast ratio (black levels), and image stability (changes in color balance and gray scale with changes in temperature and with long-term exposure to light).

The turn-on and turn-off times for molecular reorientation of the liquid crystal must be made much shorter than the video frame time of 16 ms if image "lag" or smearing is to be prevented. High address voltages, low fluid viscosities and small cell gaps favor short response times. Small cell gaps, however, can lead to brightness nonuniformities and loss of light modulation or brightness. Typical analog LCD projection displays have response times that are just under the video frame time of 16 ms. Therefore, these displays will show image lag, manifested as a blurring of the fine details in a moving image, or in a stationary image when the camera is panning rapidly.

As the display resolution increases, fixed panel or chip sizes result in smaller pixels, and fringing electric fields between neighboring pixels become a serious problem. The fringing fields lead to anomalous orientations (or disinclinations) of the liquid-crystal molecules at the pixel boundaries, resulting in degradation of contrast ratio. Video black levels become noticeably gray and images can even begin to look "soft." Fringing field effects are even more difficult to control for the new reflective LCD "chip" technologies in which pixel sizes continue to shrink as resolution increases.

Ease of setup and stable projection display performance are crucial to customer satisfaction, particularly in the demanding home theater and audio/visual rental and staging markets. Two effects lead to instabilities in LCD projectors; photodegradation products and changes in voltage threshold with changes in temperature. These can result in gray scale and color balance that are unstable over time. Both effects are exacerbated in high-brightness applications because the higher light intensities in the liquid crystal promote more rapid photodegradation and create higher liquid temperatures because of light energy absorption. Reflective LCDs fabricated on single-crystal silicon can be effectively cooled through the chip substrate, thereby providing more margin to thermal effects but not to photodegradation.

Large investments are being made each year in the development of new liquid-crystal materials having more ideal properties for a broad spectrum of digital and analog LCD projection display applications. As in the case of the CRT, steady performance and reliability improvements are anticipated each year.

## Membrane, cantilever-beam and piezoelectric-mirror light valves

Over the years, a number of light-valve technologies have been developed that rely on the micromechanical movement of mirror surfaces to defocus incident light or to "beam steer" the light around a Schlieren stop.

*Membrane light valves*—These devices have either relied on metal-coated polymer or thin metal membranes as the deformable material. In 1970, J.A. van Raalte at RCA Laboratories reported on a metal membrane light valve that did not contain organic materials and therefore could be sealed in a vacuum tube and e-beam addressed.[79] A cross section of the e-beam "target" is shown in *Figure 31* for two pixels.

The modulated e-beam deposits charge through thin openings or slots in the metal membrane onto a glass substrate. The charge deposited on the substrate electrostatically attracts the membrane, deforming it into a concave shape. The deformation acts to defocus incident light around a Schlieren stop and the light is projected to the screen. Limited performance was achieved because of the low contrast ratio, probably caused by diffracted light from the openings in the membrane.
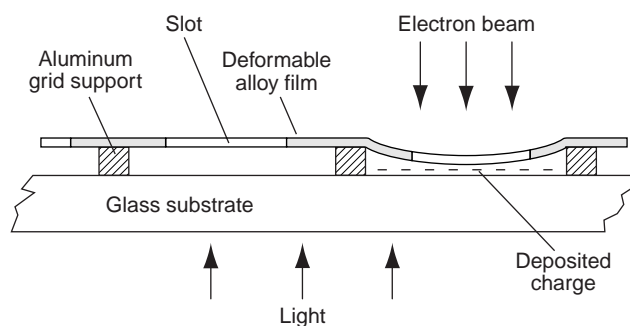


**Figure 31.** Metal membrane target.[79]

Another membrane light-valve approach was originally developed by K.P. Preston of Perkin-Elmer Corp. in 1969 for use in optical computing.[80] Called the membrane light modulator (MLM), the membrane was formed out of nitrocellulose and metallized with antimony for reflectivity. It was addressed by metal electrodes underlying the membrane air gap.

In 1990, an e-beam-addressed derivative of this technology (e-MLM) was reported.[81] Shown in *Figure 32*, the membrane is fabricated and metallized, then placed onto a charge transfer plate (pin-grid matrix). A modulated and rasterized e-beam deposits charge on pins of the charge transfer plate. A voltage drop is produced across the air gap between the pin and the metallized membrane, and the membrane deforms accordingly. Refinements to this technology were reported in 1992.[82] The e-MLM was demonstrated as both a visible display and a dynamic infrared scene projector.

*Cantilever-beam light valves*—This technology does not have the susceptibility to optical blemishes inherent in the nitrocellulose membrane light valve. Particulate contamination trapped between the membrane and supporting substrate creates "tents" in the membrane that greatly magnify the apparent size of the particles. Texas Instruments 1981 membrane-

**Figure 32.** Membrane light modulator.[81]
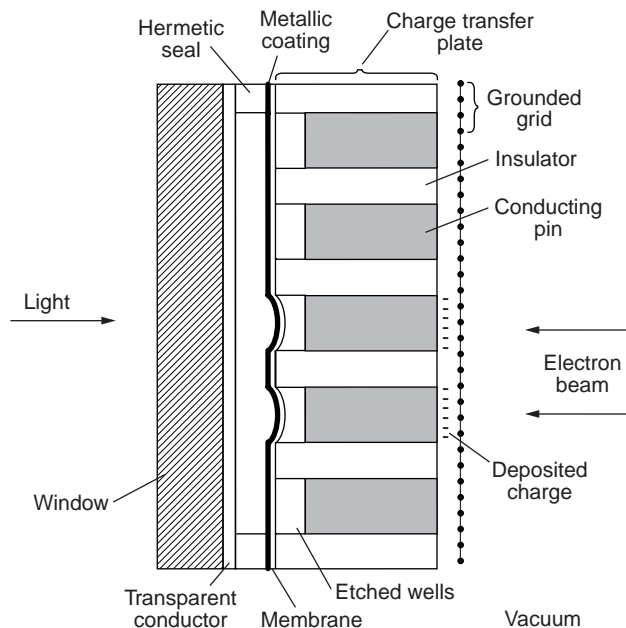


**Figure 33.** Target of Mirror Matrix Tube (one pixel).[84]

based analog DMD technology was susceptible to such blemishes and they are evident in the projected image shown later in this article. This tenting effect is avoided in the cantilever approach because the mirror surfaces can be formed monolithically over the substrate.

In 1973 Nathanson and Guldberg of the Westinghouse Corporation filed for patent applications on a technology that later became known as the Mirror Matrix Tube, an e-beam-addressed light valve.[83] In 1975 an 800 x 600 resolution projection display was demonstrated based on this technology.[84] A top view and cross section of one pixel are shown in *Figure 33.* The mirror is made of aluminized silicon dioxide (SiO$_2$) shaped in a cloverleaf pattern and supported by a silicon post over a sapphire substrate. The air gap is formed by selectively wet etching the silicon from under the SiO$_2$ prior to the deposition of a thin layer of aluminum. When the aluminum is deposited, it not only forms a mirror-like surface on the SiO$_2$, but also an electrical grid on the substrate. The sapphire substrate becomes the faceplate of the e-beam tube, with the cloverleaves on the vacuum side. The sapphire serves to transmit light from the projection lamp onto the mirrors.

In operation, a rastered and modulated e-beam charges each cloverleaf, causing the four cantilevers to be electrostatically attracted by the edge forces toward the aluminized grid and to bend a maximum of approximately 4 degrees. Light is beam steered around a cross-shaped Schlieren stop according to the cantilever deflection angle. Because the cantilevers of each cloverleaf bend by 45 degrees relative to their edges, diffracted light is rejected by the cross-shaped Schlieren stop and the beam-steered light is passed. The result of this "45-degree discrimination" architecture is higher contrast ratio. This technique is employed in current DMD architectures.

Nevertheless, disappointing contrast ratios of 15:1 were demonstrated. Perhaps this was due to the fact that the electrostatic edge forces produced not only a bending at the hinge, but also produced some curvature to the cantilevers so they no longer acted as planar mirrors.

*Piezoelectric-mirror light valves*—This class of light valves depends for its operation on piezoelectric materials that expand or contract depending on the polarity of the applied voltage to produce rotation of a mirrored surface. Such a light-valve technology was developed by Aura Systems Inc. in the early 1990s and is called the Actuated Mirror Array (AMA). An early version is described in a patent that was awarded to Aura Systems in 1993.[85] Later, AMA technology

**Figure 34.** Actuated Mirror Array concept (bulk approach).

was licensed and further developed by Daewoo Electronics Company Limited. One such "bulk" implementation of the AMA is shown in *Figure 34*.

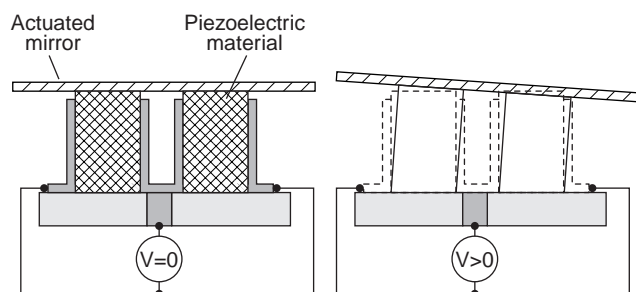Two piezoelectric posts are addressed with opposite polarity voltages so that when a voltage is applied, one post expands vertically, while the other contracts. The action of the posts causes an overlying mirrored surface to tilt or rotate. The reported mirror tilt angle is ±0.25 degrees at 30 volts. Gray scale is achieved by analog operation of the tilting mirrors in a Schlieren optical configuration.[86]

Limitations of the bulk AMA approach include a difficult hybrid fabrication process and limited tilt angle. A thin-film approach was proposed in 1997 that would integrate the piezoelectric material onto a silicon address circuit and produce much larger tilt angles.[87] Cantilever beams acting as mirrors would be driven by thin-film piezoelectric drivers. It is not known whether this concept has been demonstrated in a working display system.

## The Digital Micromirror Device

Almost 21 years ago, in November 1977 a small U.S. Government-funded program was initiated in the Central Research Laboratories (CRL) of Texas Instruments to build a CCD-addressed, membrane-based spatial light modulator for optical processing applications. Later called the Deformable Mirror Device (DMD), this technology was to be the forerunner of the current Digital Micromirror Device (also DMD) invented ten years later in 1987.

Only by its initials does the original technology bear any resemblance to the current DMD technology that forms the basis for Texas Instruments Digital Light Processing (DLP) projection display business. The Deformable Mirror Device was analog, required high-voltage addressing and was fabricated with a hybrid process. The Digital Micromirror Device is digital, uses standard 5-volt addressing and is fabricated with a monolithic, CMOS-compatible process.

The following is a brief account of how Texas Instruments took advantage of the digital electronics revolution to develop the world's first high-performance light valve on single-crystal silicon. TI's entrepreneurial spirit and long-term financial commitment, the innovative skills, dedication and perseverance of its employees, a little luck, timing, …all contributed to the development and commercial success of this technology.

***The analog decade (1977-1987)*** —In November 1977 the author and two other researchers in CRL began work on a U.S. Government-funded program to develop a spatial light modulator for optical signal processing applications, such as pattern recognition. TI bid on the program on the basis of its strength in CCD technology, particularly its CCD technology used for night vision applications. In that application, the CCD substrate was thinned and imaged from the backside (opposite the charge transfer electrodes) with electrons emitted from an infrared-sensitive photocathode.

It had been proposed that a membrane-based spatial light modulator be fabricated on the backside of a thinned CCD address circuit. The CCD would work in reverse. Instead of reading out a charge pattern corresponding to an image, a charge pattern would be read into the device and then be transferred across the thinned silicon substrate to the backside. The charge would modulate the potential across the air gaps of the membrane pixels and thereby deflect them. But it soon became apparent that a more manufacturable approach would be required.

The approach that was developed is shown in *Figure 35*. The metallized membrane was based on the technology used by Preston at Perkin-Elmer. It was fabricated from nitrocellulose and metallized with antimony (later to be improved by alloying with
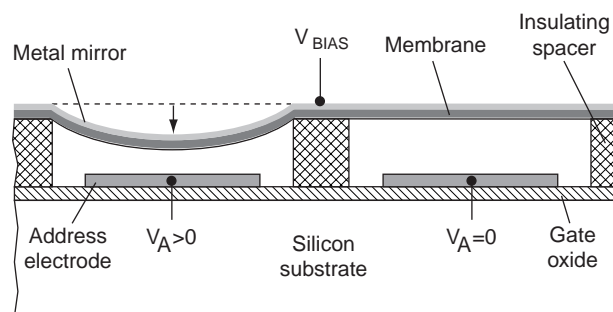


**Figure 35.** Membrane Deformable Mirror Device (simplified cross section).

bismuth). The membrane was cast in its liquid state onto the surface of clean water and picked up with a casting ring, dried and metallized before being placed onto the address circuit. The address circuit consisted of an array of n-channel transistors with one transistor for each pixel. Its function was similar to the way liquid- crystal devices are addressed today by single-crystal silicon address circuits. Polysilicon material served a dual purpose, as the gate of the transistor and as a sacrificial spacer.

By 1979 a 16 x 16 pixel array was demonstrated. Although this device was to be used in optical signal processing applications, for test purposes it was desirable to show the mirror deformation. Schlieren projection optics were developed to convert mirror deformation into brightness variations. Early on, the DMD was associated with displays, and many viewed the DMD program as an effort to produce a "display on a chip." By 1981 a 128 x 128 pixel array had been demonstrated. An image from an early device is shown in *Figure 36*. By 1983 lower defect counts were achieved, sufficient for optical processing applications.[88,89]

In 1980 W. Ed Nelson of Texas Instruments proposed that the DMD be used as a "light bar" to replace the laser polygon scanner in an electrophotographic (or "xerographic") application. Although it

would soon become apparent that the membrane-based DMD was unsuitable for the high aspect ratio, linear pixel arrays required in printing, the investigation launched a part of the DMD effort in a new direction. This new approach sought a way to build a monolithic cantilever-beam DMD over a single-crystal silicon address circuit. This internally funded focused effort was to consume the next four years and would result in the dispiriting conclusion that an *analog* DMD (monolithic or not) would never be suitable for the printing application!

In 1983 a new, low-temperature fabrication process was developed. For the first time, the fabrication of a micromechanical structure directly over a completed metal-oxide-silicon (MOS) address circuit, including its aluminum interconnects, was possible. At the time, there were two technologies for building micromechanical cantilever beam structures on single-crystal silicon as shown in *Figure 37*. The first approach (a) used $SiO_2$ for the mechanical element and a p-type epitaxial silicon layer as the "sacrificial" layer, grown over a p+ buried layer that acted as an etch stop.[90] The epitaxial layer was anisotropically wet etched in ethylenediamine and pyrocatechol (EDA). The second approach (b) used polysilicon as the mechanical element and an $SiO_2$ layer for the sacrifi-



**Figure 36.** 128 x 128 membrane DMD (first projected image, 1981). Blemishes are examples of "tenting."



a) **P-Epitaxial sacrificial layer**
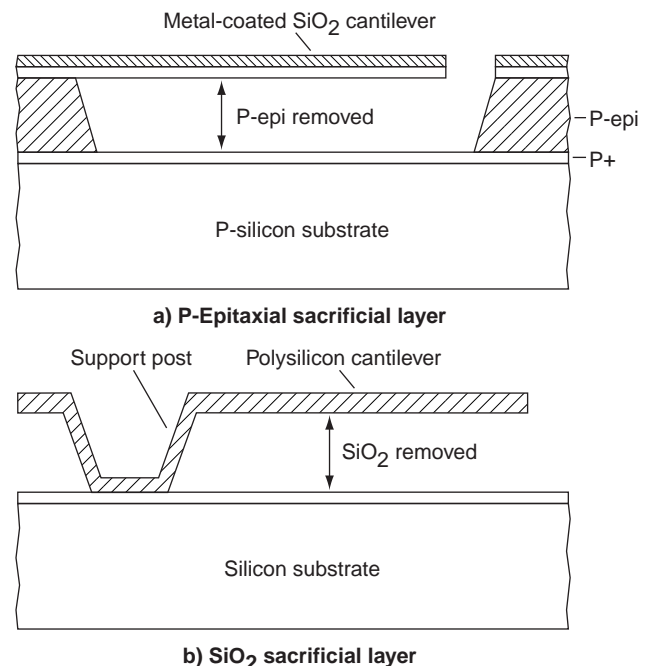
b) **SiO$_2$ sacrificial layer**

**Figure 37.** High-temperature micromechanical process technologies (circa 1983).

cial layer or spacer.[91] The spacer was removed by wet etching in HF acid to form the air gap.

Both approaches involved process temperatures greater than what could be tolerated by aluminum, which is used as the interconnect material in the silicon address circuit. The first approach also removed the single-crystal silicon, precluding the fabrication of transistors directly under the mechanical element.

To overcome these significant limitations, the low-temperature DMD fabrication process shown in *Figure 38* was conceived. A planarizing photoresist layer (spacer) is spun over the MOS address circuit including its aluminum interconnects. The photoresist acts as the sacrificial layer. It is patterned with holes for what will become support posts and hardened to prevent it from melting later during the process. Aluminum for the micromechanical elements is sputter deposited and patterned using a plasma or "dry" etch. It covers the sidewalls of the holes to form support posts and electrical contacts to the underlying metallization layer. To complete the process, the organic photoresist sacrificial layer is stripped in a special plasma chemistry containing oxygen and fluorine which minimizes the process temperature (so-called undercut process).

This extremely simple low-temperature DMD process is accomplished at less than 200 °C and preserves the integrity of the underlying address circuit. Its advantage over existing process technologies was

to enable the fabrication of a close-packed array of aluminum mirrors and hinges directly over a completed MOS address circuit, including the aluminum interconnects. This breakthrough processing concept enabled both analog and digital DMD architectures and was a major factor leading to the industry's first commercially successful "display on a chip" technology.

In 1984 a linear DMD test array was designed for the printing application. It was based on the new low-temperature process technology and consisted of 2400 cantilever beams in a staggered line array as shown in *Figure 39.* Each square aluminum cantilever had a hinge in the corner that allowed bending to occur at 45 degrees relative to the edges of the cantilever for improved contrast ratio. This was basically the same approach as in the Westinghouse Mirror Matrix Tube described earlier.
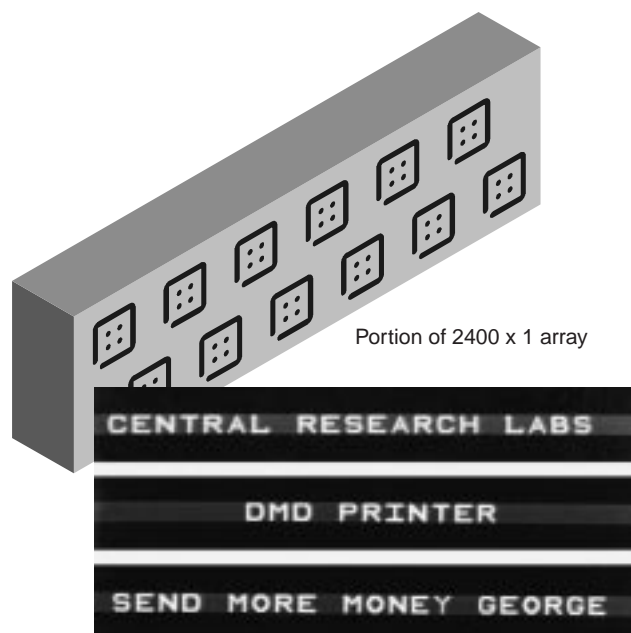


**Figure 39.** Cantilever-beam DMD print samples on film.

An aluminum address electrode under each cantilever acted to electrostatically attract the cantilever mirror. The address electrodes were hard wired in patterns so that the test chip would require no transistors. The stable deflection range was up to four degrees at 30 volts. Beyond four degrees, the tips of the beams would spontaneously touch down and usually stick to the surface!

The first printing using the new 2400 x 1 DMD was done by scanning film past the projected image



**a) Before undercut**



**b) After undercut**

**Figure 38.** Low-temperature DMD process.

of the pixels. Print samples are shown in Figure 39 including an appeal to a TI executive for more money to support the technology! Later, print samples were made on plain paper using an electrophotographic process, in which the DMD array acted to expose a photoreceptor drum.

Soon it became apparent that the hinges of the original cantilever design were too stiff. What was required was a thin hinge for compliance and a thicker cantilever beam to yield a flat mirror. In an ordinary multilevel metal process, the hinge metal would be patterned and plasma etched first, followed by the beam metal. But plasma chemistry is often not very kind! The byproducts of the plasma etching contaminate and roughen the photoresist spacer, making it unsuitable for further metal deposition. The challenge became how to "pattern" the hinge but not really etch it until later, after the beam metal is etched. A new "buried-hinge" process was developed in 1985 that met the challenge, and it has been used ever since for the hinge/beam process.

The buried-hinge process shown in *Figure 40* begins with the deposition of hinge metal over the photoresist spacer, followed by a plasma deposition of $SiO_2$. The $SiO_2$ is then patterned in the shape of the hinge, with appropriate overlaps to the subsequent cantilever-beam pattern. Then the beam metal is deposited, thereby burying the $SiO_2$ hinge pattern. A photoresist pattern in the shape of the beam is formed over the beam metal. Finally a single plasma aluminum etch is used for both the beam metal and hinge metal. The photoresist masks the beam metal and prevents it from etching. The $SiO_2$ does the same for the hinge, acting as a buried etch stop. The $SiO_2$ is plasma-stripped from the hinges prior to the photoresist spacer strip that creates the air gap.

In 1986 it was hoped that the combination of the low-temperature DMD and buried-hinge processes would yield DMD pixel arrays that met requirements for the electrophotographic printer application, including angular deflection uniformity of the beams across the array. But after a significant effort, the angular uniformity requirement could not be met. Process-induced surface stresses and residues on the hinges were causing them to deviate from flatness in the non-energized state leading, to nonuniform angular deflections when energized. The hinge stress also exhibited an "aging" effect that caused the angular deflections to be unstable with time and temperature.

After many frustrations and failures, it became apparent that the *analog* nature of the DMD's



**a) After oxide hinge mask patterning**



**b) After beam metal photoresist pattern**



**c) Completed structure**
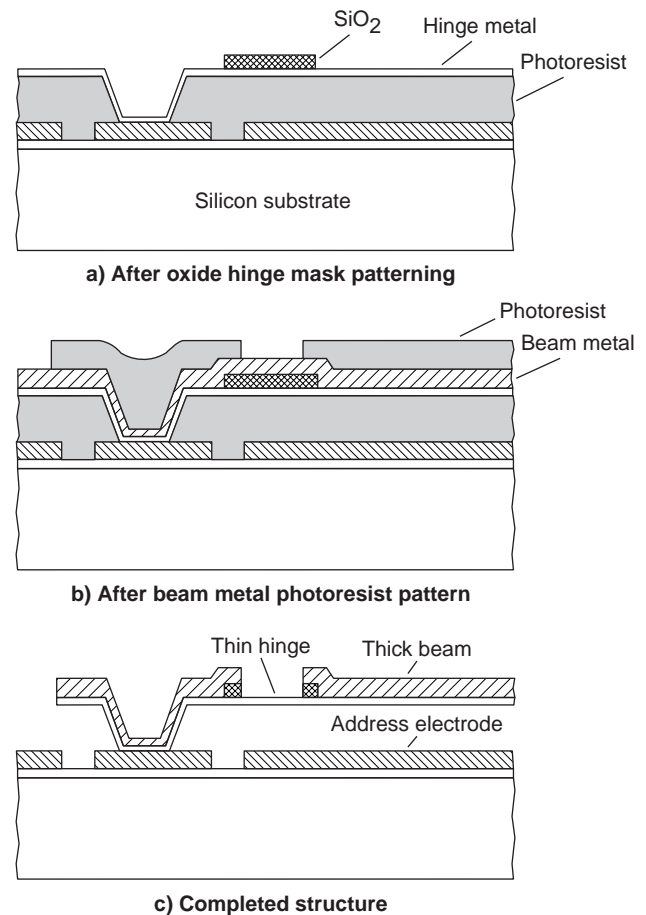
**Figure 40.** The buried-hinge process for DMD.

mechanical structure would preclude it from ever becoming a commercially viable technology for printer applications.

***The digital decade (1987-1997)***—By early 1987 the time had come to make a decision—abandon the DMD as a viable approach for electrophotographic printing or develop a new architecture that was not sensitive to hinge surface stresses and the aging effect. As often happens, desperation breeds innovation. By the end of 1987 a breakthrough device concept was conceived and demonstrated called the bistable deformable mirror device or bistable DMD.[92-95]

The bistable DMD concept is shown in *Figure 41*. Instead of cantilever hinges, the beam is supported by a pair of torsion hinges. The torsion beam rotates until its "landing" tip touches a landing electrode pad that is at the same potential as the beam. Instead of analog deflection angles determined by a balance of forces, the bistable DMD has digital deflection
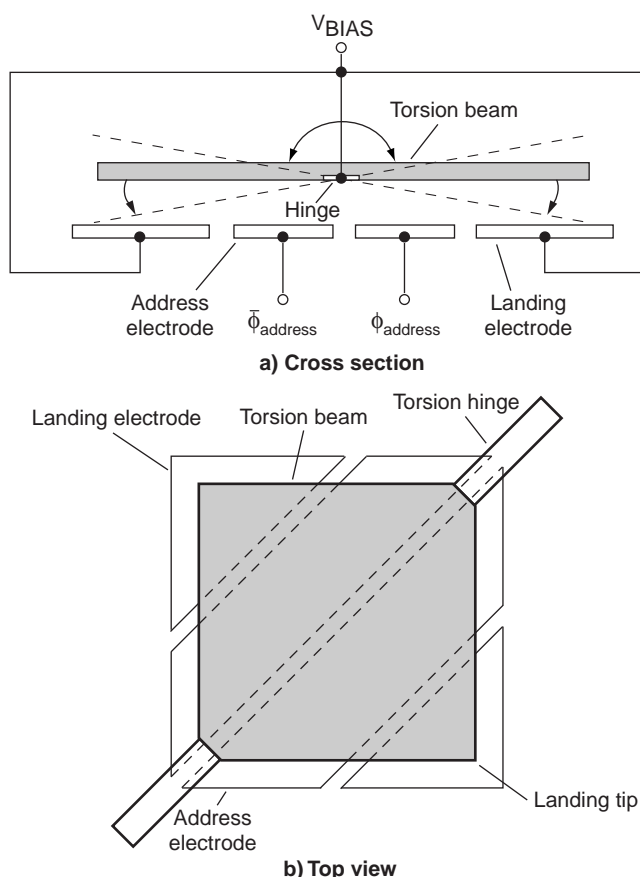
**Figure 41.** The bistable DMD concept.



**Figure 42.** DMD optical switching principle.

angles because the beam lands. The angle is determined by the spacer air gap and the length of the torsion beam from it axis of rotation to its landing tip. The direction of rotation is selected by a pair of address electrodes on either side of the rotation axis. Complementary voltage waveforms ($\phi_{address}$, $\overline{\phi}_{address}$) are applied to these electrodes by an underlying memory cell. A bias voltage applied to the beam makes the beam energetically bistable. The result is lower address voltages, permitting larger deflection angles.

In comparison to the old analog DMD technology, the bistable DMD's advantages are (1) larger rotation angles (± 10 degrees), (2) precise rotation angles unaffected by environment or age, and (3) lower address voltages compatible with standard 5-volt MOS transistor technologies.

For the first time, larger rotation angles enabled the use of "darkfield" projection optics as opposed to the Schlieren optics used in the oil-film projectors and other light valves. As shown in *Figure 42*, the DMD acts as a fast digital light switch. The light from

the projection lamp is rotated completely out of the pupil of the projection lens so that no Schlieren stop is required.

The first test chip based on the bistable DMD (or just DMD as we shall call it from now on) was a 512 x 1 linear array (four staggered rows, 128 x 4). It had hard-wired address electrode patterns designed for testing the concept and implementing the first digital printing demonstration. Testing commenced in November 1987, and all of the DMD's digital benefits were realized! The first photos of device operation under a darkfield and brightfield microscope are shown in *Figure 43*, along with an early print sample. Soon, an expenditure of 30 cents was made to purchase red and blue tinted transparent plastic that was placed in the annular illumination ring of a darkfield microscope objective. This provided a way of distinguishing the positive and negative rotation directions (plus = red, minus = blue) and was the first demonstration of colored images!

As testing continued, the initial excitement over the first results began to fade. Although not unexpected, after only a few million landings, the landing tips began to stick to the landing pads. This phenomenon was later identified as adhesion caused by a
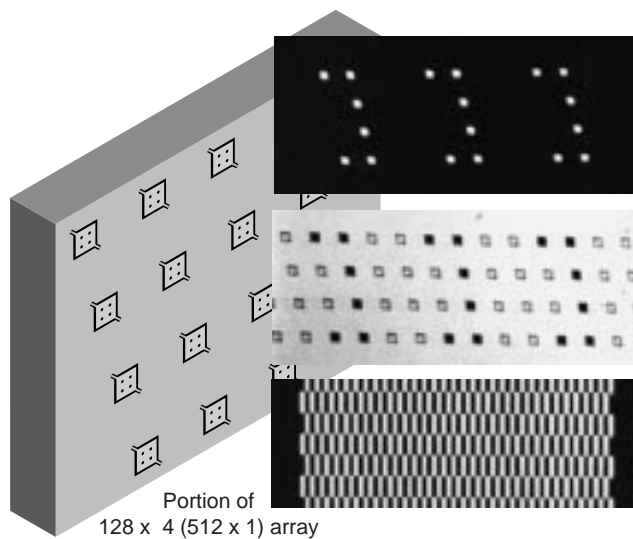
**Figure 43.** First bistable DMD (darkfield and brightfield photomicrographs and electrophotographic print sample).

combination of the capillary condensation of water and van der Waals forces (surface forces). After many long hours in the lab by the author, a solution to this problem was implemented called electronic "reset." In this technique, a voltage pulse is applied to the beam bias that deforms the beam, stores energy and then releases it to "spring" the landing tip away from the surface.

With this reset technique in hand, the 512 x 1 test device was integrated into a printer test bed, and in 1988 the first digital print samples were generated. The results were encouraging, but more difficulties had to be overcome before the new digital light-valve technology could be considered worthy of consideration for incorporation into a printing product. Although electronic reset had provided a way of releasing the beam tips from the surface, it still did not provide the reliability necessary for a product. It was not until early 1990 that a breakthrough occurred, a way of providing lubrication (or passivation) to lower the adhesive levels and the amount of mechanical wear that was occurring during reset.

The method that was adopted was based on a discovery made in the last century, that certain whale oils are autophobic. When an autophobic oil is placed on a bearing surface, an impurity in the oil forms a surface film that the oil will not wet, reducing its likelihood of creeping away from the bearing. The impurity was determined to be a fatty acid that was form-

ing an oriented monolayer on the bearing surface, resulting in a low-energy surface (or one having low adhesive forces). This same principle was applied to the DMD with a few important modifications. The method of deposition was by vapor, rather than liquid, and the material was fully fluorinated to provide the lowest possible level of adhesion, only one-quarter that of Teflon™-like surfaces. Combining the passivation process and improved packaging techniques led to the reliability necessary for using the DMD in a printing product.

In late 1988 product development was initiated to build the world's first electrophotographic, high-speed airline ticket printer. It would be based on a DMD "exposure module." The team to develop the exposure module was led by Ed Nelson, who eight years earlier had first proposed a DMD printer, and who had since championed and led the development activities for the DMD printing application. An 840 x 1 DMD array was designed to print 240 dots per inch on a 3.5-inch wide ticket coupon at 40 coupons per minute. Introduction of this product in late 1990 represented the first commercialization of a micromechanical light-valve technology in history.

During this period of intense product development, Jeffrey Sampsell of TI's Central Research Laboratories led a small team to explore the possibility of using the DMD for projection display applications. Interest in the DMD spread outside of Texas Instruments. In 1989 a joint development program with Rank-Brimar Limited (currently Digital Projection International) and a high-definition display contract with DARPA (Defense Advanced Research Projects Agency) were initiated. These programs formed the beginnings of what would later be a massive, internally funded effort by TI to bring DMD projection display technology to the market.

DMD projection display technology started from humble beginnings with a two-line demonstration in 1990! A pair of DMD printer chips were mounted in the same package to represent two lines in a digital display. Demonstration optics were assembled that included a spinning color disc that enabled the time-multiplexing of red, green and blue light onto a single DMD chip. Gray scale was achieved using a technique called binary-weighted pulsewidth light modulation, illustrated in *Figure 44*. Because the DMD is a digital light switch, its only capability is to turn light on or off. But because of the high switching speed, it was possible (during each video frame time) to produce a burst of digital light pulses of varying dura-
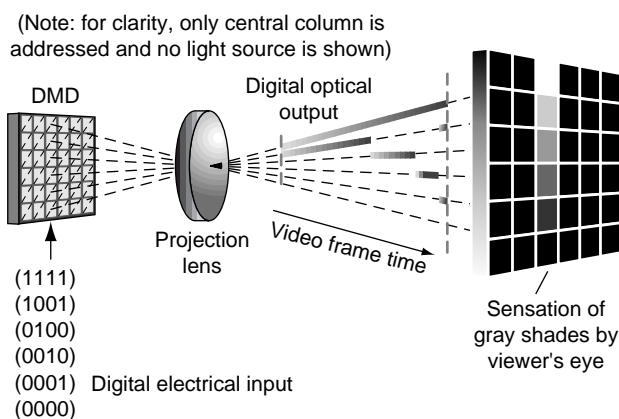
(Note: for clarity, only central column is addressed and no light source is shown)

DMD

Digital optical output

Projection lens

Video frame time

Digital optical output

Sensation of gray shades by viewer's eye

(1111)
(1001)
(0100)
(0010)
(0001)  Digital electrical input
(0000)

**Figure 44.** DMD binary-weighted pulsewidth modulation (4-bit, 16 gray-level example).

tions that led to the sensation of gray scale as perceived by the viewer.

Current DMD architectures have a mechanical switching time of ~15 μs and an optical switching time of ~2 μs. Based on these times, 24-bit color (8 bits or 256 gray levels per primary color) is supported in a single-chip projector while 30-bit color (10 bits or 1024 gray levels per primary color) is supported in a three-chip projector. Twenty-four-bit color depth yields 16.7 million color combinations while 30-bit color depth yields more than 1 billion color combinations. Even higher bit depths can be achieved by multiplexing techniques.

Unlike LCD technology, in which the switching times are ~10 ms, the DMD has no image lag from one frame to the next and therefore moving objects are not blurred. Because the gray scale of the DMD is determined by time division, it is accurate and stable. By comparison, gray scale in an LCD-based projector is determined by the analog voltage level delivered by the address transistor and the analog characteristics of the liquid crystal material. Temperature and photodegradation can therefore have an adverse effect on LCD image stability.

While two-line DMD displays were being viewed with great curiosity, the first true DMD display chips were being developed. The first was a 768 x 576 (PAL format) resolution chip with full transistor addressing. The second was a high-definition 2048 x 1152 demonstration chip having a fixed-image capability "wired" into its substrate. It seemed during 1991 there was a surge in the number of "true believers" who could make the leap of faith from two-line to 1152-line DMD displays. Excitement over the DMD

was contagious and extended to the upper levels of TI management.

Acting on this excitement, Texas Instruments formed the Digital Imaging Venture Project (DIVP) in December 1991 and transferred the DMD from the Central Research Laboratories into this new organization. An infusion of talent and capital into DIVP led to many improvements in the DMD chip architecture, fabrication, packaging and testing, system architecture and optics. The name of the device was changed from Deformable Mirror Device to Digital Micromirror Device to more accurately describe its function compared to the original membrane-based analog DMD.

During the first year of DIVP's existence, both chip and system level advancements were being made. A prototype 768 x 576 resolution DMD projection system was demonstrated in May 1992, projecting static images, shown in *Figure 45*. The projector was based on a single DMD chip and time-multiplexed color. This marked a major milestone in the history of projection display technology, the first full-resolution color demonstration of a "display on a chip." *Figure 46* shows a projected image of an improved DMD architecture demonstrated in 1993. The light shield has been removed and the field of view of the projection lens has been increased to show the chip perimeter, including the bond pads and wires. This image dramatically illustrates the display-on-a-chip nature of DMD technology. In spite of the historical significance of the May 1992 demonstration, much



Portion of 640 x 480 array
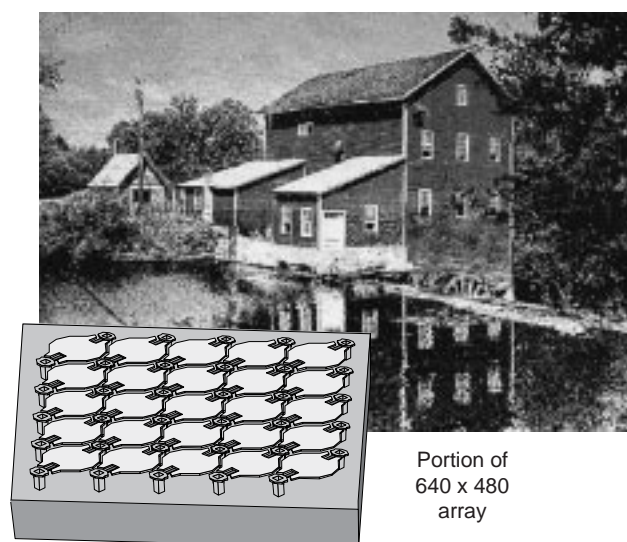
**Figure 45.** First full-color DMD images, May 1992.

remained to be improved in terms of pixel defects, contrast ratio and reliability.

At the chip level, the first major advancement was to improve the contrast ratio of the DMD. In the orig-inal architecture, shown in Figure 45, the beam (mirror) and hinges were coplanar. Light scattering from the hinges and support posts lowered the contrast ratio. The active area ratio and hence the brightness of the display were also was reduced. A new structure was developed that hid the micromechanical structures under the mirror. It was given the name "hidden hinge." This was the first in a series of architectural improvements shown in *Figure 47*. In this concept, the beam or ("yoke") supports an overlying 17 μm x 17 μm mirror.

In 1993 the hidden hinge concept was demonstrated in a 768 x 576 resolution DMD projection system that showed significant improvements in contrast ratio and light efficiency over earlier systems.[96] *Figure 48* shows a close-up view of early hidden hinge DMD mirrors operating in a scanning electron microscope. *Figure 49* shows the mirror surface of the current DMD. Because the gaps between the mirrors are so narrow, the projected image of a DMD appears "seamless" or almost film-like, i.e. the pixel structure is almost invisible. The seamless appearance of DMD images has become a hallmark



**Figure 46.** DMD front projection display showing entire chip area (768 x 576 array, 640 x 480 image).



**Figure 47.** Evolution of DMD pixel architecture.

**Figure 48.** SEM video images of operating DMD (early version).



**Figure 49.** SEM photomicrograph of current DMD mirrors.

of DMD-based projection displays and stands in contrast to transmissive LCD display technology where the pixel structure is readily apparent.

Also in 1993, as an outgrowth of the original DARPA contract, a high-definition, fixed-image 2048 x 1152 resolution, three-chip display was demonstrated. The DMD chip contained no address transistors, only hard-wire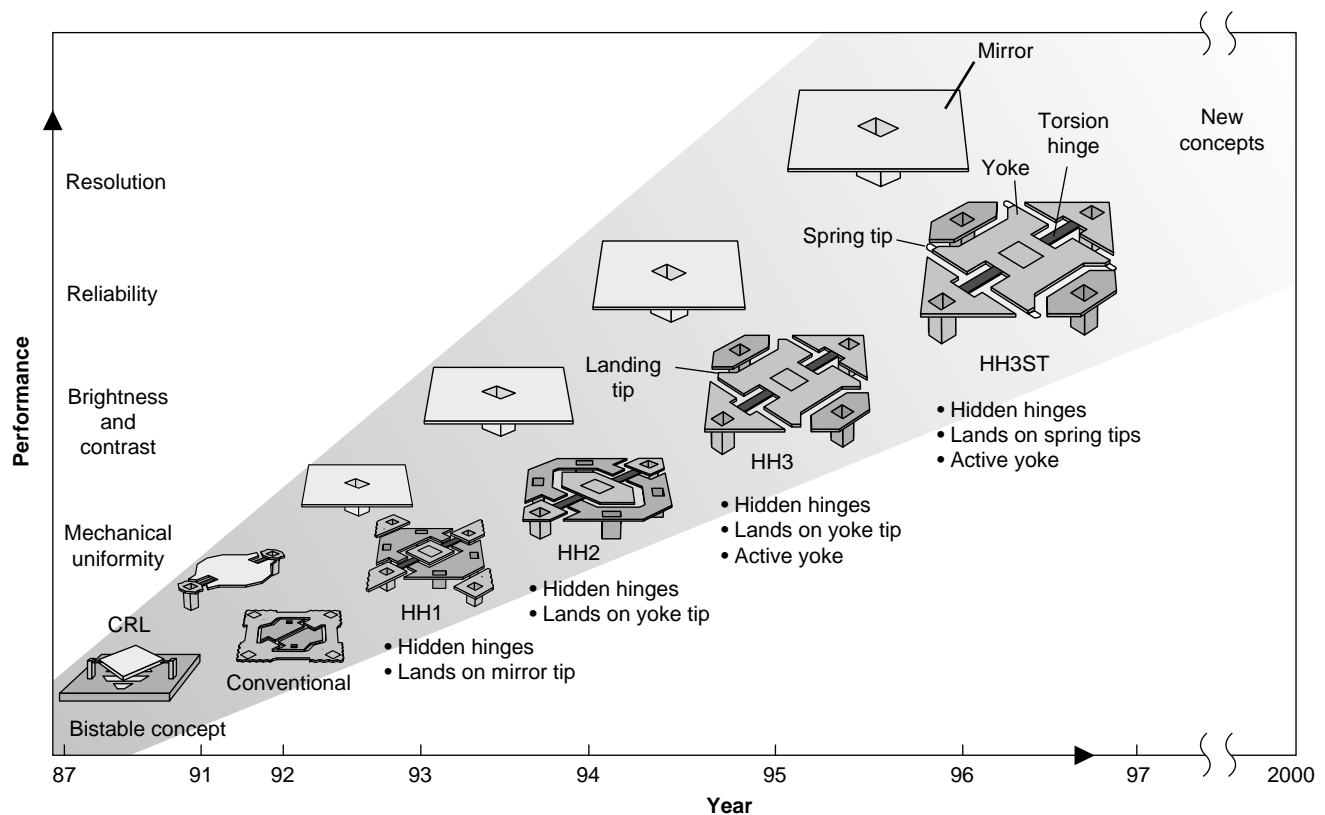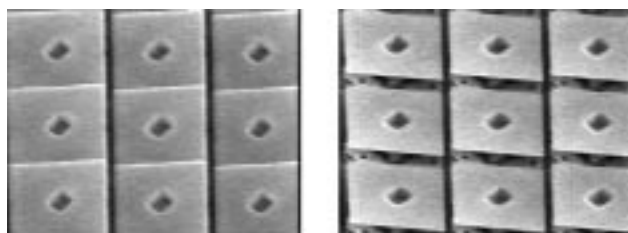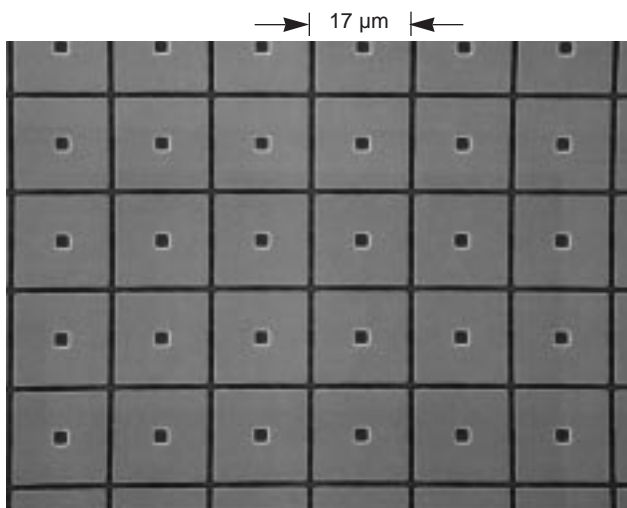d patterns of address electrodes that permitted fixed images to be projected. This proof-of-concept demonstration showed the feasibility of manufacturing large-area DMD superstructures, tested the optical design and provided a glimpse of high-definition DMD images. The lessons learned would be applied to the demonstration in 1994 of a 2048 x 1152 resolution, three-chip DMD-based projection system that incorporated full transistor addressing and projected static images.[97,98]

In 1994 DIVP engineers demonstrated the world's first all-digital projection display from source to eye.[99] The digital source material was derived from a telecine transfer of movie film to digital tape. This demonstration showed that DMD-based projection

systems had unique capabilities for digital fidelity and stability found in no other projection display technology. It was apparent that this all-digital display technology needed a name that described it at the highest level of its functionality. The name chosen was Digital Light Processing or DLP.

Architectural modifications of the DMD pixel continued and not only improved the performance but also enhanced reliability. As shown in Figure 47, additional versions of the basic hidden hinge structure (HH1) were developed. The first of these (HH2) extended the yoke structure so that the yoke rather than the mirror landed. In 1994 an improved version (HH3) widened the yoke so that it not only was the landing structure, but it also was electrically active to provide greater electrostatic efficiency.[100-102]

In 1995 "spring tips" were added to the landing tips of the yoke.[103] These were made from the hinge material and provided additional energy storage for improved reset reliability. *Figure 50* shows architectural details of the HH3 spring tip architecture for two pixels, one with the mirror tipped +10 degrees and the other –10 degrees. In *Figure 51* a scanning electron microscope image of the yoke and hinge levels is shown before the mirrors are processed. The first spacer has been removed to reveal the underlying metal level (metal 3) just above the CMOS transistor circuitry.

Concurrent with these architectural improvements were those in the areas of wafer process improvements and particle controls, packaging, hinge materials, lubrication, drive waveforms and high-speed automated testing.[104] Together, these improvements
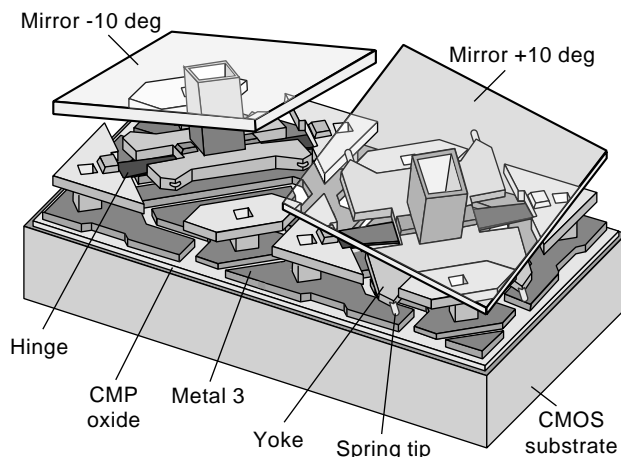


**Figure 50.** Two DMD pixels (mirrors are shown as transparent).
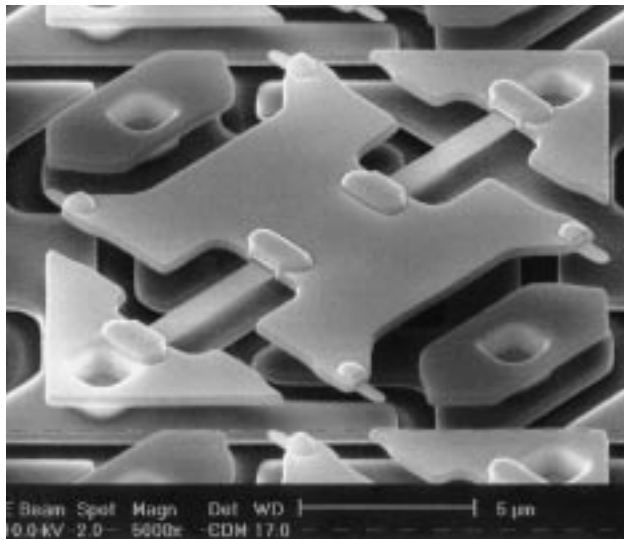
**Figure 51.** SEM photomicrograph of yoke and hinge levels (before mirror processing). First spacer has been removed.

led to the demonstration of the performance and reliability necessary to commercialize the DMD.[105] On the systems side, there were pioneering improvements in the image processing algorithms and optical architectures necessary to ensure the maximum performance advantage of the Digital Light Processing system shown in *Figure 52*.[106-108]

Three types of DLP projection systems had been developed by 1996, differentiated by the number of DMD chips–one, two, or three *(Figure 53)*. The choice depends on the intended market application and is based on a tradeoff between light utilization efficiency, brightness, power dissipation, lamp technology, weight, volume, and cost. The single-chip and two-chip systems rely on the time multiplexing of color, a unique feature of DMD technology arising from the fast switching time of the mirrors. The slower response time of analog-based LCDs precludes all but a three panel architecture.

The three-chip projector has one chip for each of the primary colors, red (R), green (G), and blue (B). Light from an arc lamp is focussed onto an integrator rod, that acts to homogenize the light beam and change its cross-sectional area to match the shape of the DMD. The white light (W) then passes through a total internal reflection (TIR) prism. The prism adjusts the incidence angle of the light beam onto the DMD so the beam can be properly switched into and out of the pupil of the projection lens by the rotating action of the DMD mirrors (refer to Figure 42). A set of dichroic color-splitting prisms splits the light by reflection into the primary colors and directs them to the appropriate DMD. The modulated light from each DMD traverses back through the prisms, that
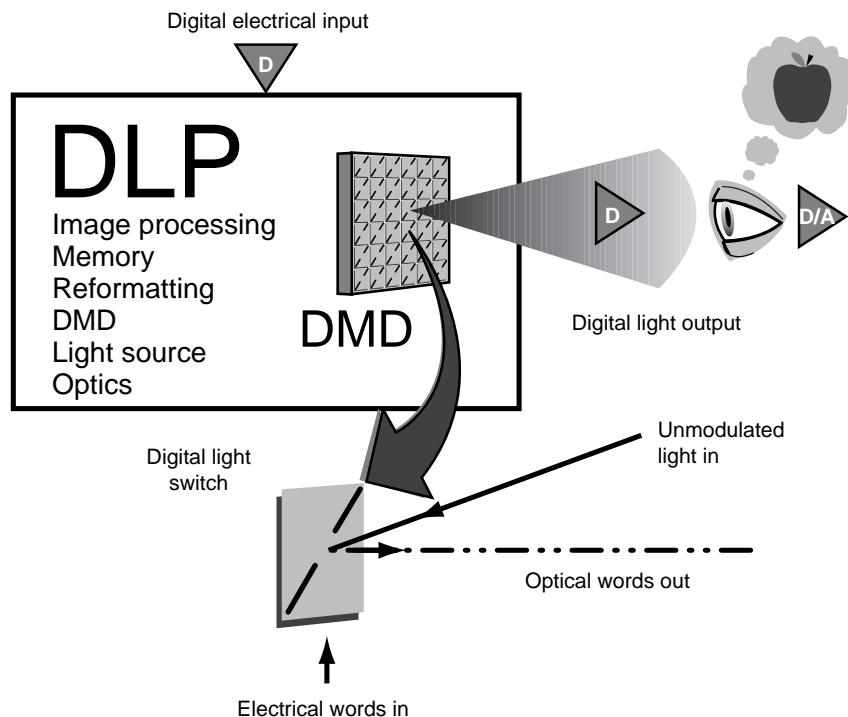


**Figure 52.** Digital Light Processing system.
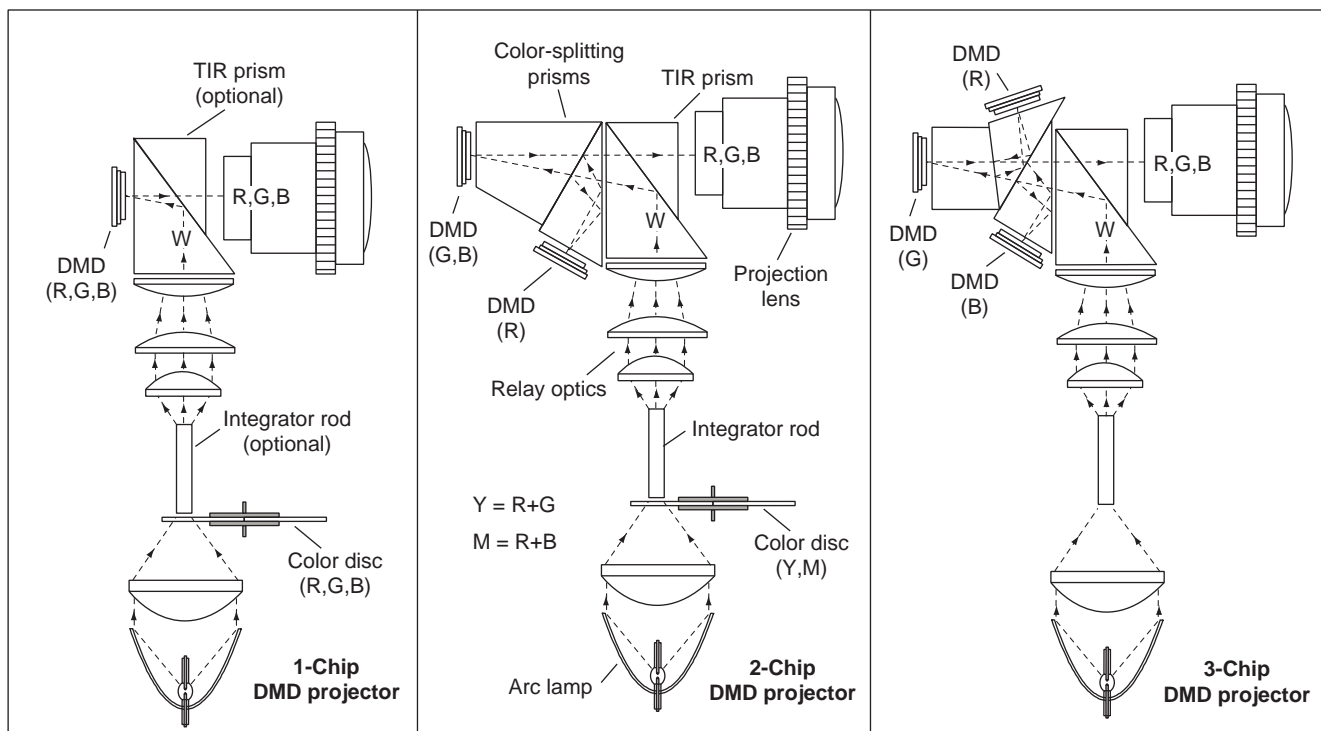
**Figure 53.** DLP family of projectors (Note: to clearly illustrate the complete light path, TIR prisms are rotated 45 or 90 degrees with respect to color-splitting prisms, compared to actual systems).

now act as a combiner for the primary colors. The combined light (R,G,B) passes through the TIR prism and into the projection lens. It is not reflected at the TIR prism because the angle of incidence has been reduced below the critical angle for total internal reflection.

The two-chip projector has a spinning color disc that alternately passes yellow light (R+G) and magenta light (R+B). The dichroic color-splitting prisms direct R continuously to one chip and G and B alternately to the second chip.

The single-chip projector has a color disc that alternately passes R, G, B to the DMD chip. Although the singe-chip diagram in Figure 53 includes an integrator rod and TIR prism, these may be omitted in lower cost designs. Without a TIR prism, the projection and illuminating lens will mechanically interfere unless the projection lens is offset from the center of the DMD.

Each projector has its own benefits and tradeoffs. The single-chip projector is self-converged, lower in cost and permits the very lightest portable designs. The two-chip projector provides greater light efficiency and is well suited in applications requiring the very longest lifetime lamps that may be spectrally

deficient in the red. The three-chip projector has the highest optical efficiency and is required in the brightest large-venue applications such as trade shows and public information displays.

By early 1996 DLP technology was ready for commercialization. The Digital Imaging Venture Project, no longer a venture, was renamed Digital Imaging. A number of market leaders in the projection display industry had been working with Digital Imaging on DLP-based projection display products for several years. At first, display "engines" were sold to these market leader OEMs (original equipment manufacturers) for incorporation into their final products. Later, Digital Imaging would also sell DMD chip sets together with DLP digital image processing and formatting boards.

The first DLP-based projection display products were introduced to the market in April 1996.[109] These products were VGA (640 x 480) resolution, portable projection displays based on a single chip and time-multiplexed color. Soon SVGA (800 x 600) resolution products were brought to the market.[110] In late fourth quarter 1996 two-chip products were introduced for home theater. In early 1997 two-chip systems for videowall applications and three-chip, high bright-

**Figure 54.** Large-venue DLP-based projector.

ness systems for home theater and large-venue applications *(Figure 54)* were brought to the market.[111]

***The DMD today***—Today, just two and one-half years after the first product introduction of DLP-based projection displays, more than 100,000 DLP subsystems have been shipped to customers. DMD reliability has been demonstrated to be in excess of 100,000 operating hours (more than one trillion mirror cycles).[112]

More than 20 Digital Imaging customers, virtually all of the industry's most respected names, are selling DLP-based products in various electronic projection display markets including mobile, stationary conference room, home theater, videowall and large venue[113]. Systems with resolutions of SVGA (800 x 600) and XGA (1024 x 768) are available. Prototype SXGA (1280 x 1024) resolution systems have been demonstrated and will be introduced to the market in 1999.

The unparalleled versatility of DMD technology has led to differentiated products ranging from one-chip ultraportable to three-chip ultrabright projectors. Two-chip projectors with ultra-long lifetime lamps are found in between. In the mobile market, a one-chip DLP-based ultraportable projector with 500 ANSI lumens of brightness and weighing 7 pounds is currently the best-selling product in its class. Two-chip DLP-based video cubes for the videowall market are setting new standards for edge-to-edge uniformity and stability in an application where color and gray scale matching from cube to cube is critical. Two- and three-chip DLP-based home theater systems are found in both front and rear projection con-

figurations. They bring clear, film-like images to the home and even double as large-screen PC monitors. In the ultrabright, large-venue market, three-chip DLP-based projectors with up to 6500 ANSI lumens of brightness and XGA resolution are widely accepted as the industry standard for digital fidelity, stability and ease of setup.

Texas Instruments and its manufacturing partners have received numerous technology and product awards for the DMD and DLP-based projectors. Recently, the Academy of Television Arts & Sciences awarded Emmys for Outstanding Achievement in Engineering Development to Digital Projection International (longest-standing customer for DLP subsystems), Brian Critchley of Digital Projection, Texas Instruments, and the author. These Emmys are the first ever awarded for a projection display technology.

## Summary

The first large-screen electronic projection displays were developed in the early 1940s. The CRT, oil-film projector and the forerunner of the modern laser projector were the ancestors of today's improved CRTs, light-valve projectors and the laser projector. Light-valve projectors were developed to overcome the basic limitation of the CRT, its lack of brightness. Light valves address this fundamental limitation by separating the light source and the means of controlling the light. Light valves are categorized by the address technology, the light valve or control layer, and the use of any intermediate conversion technology between the addressing scheme and the control layer.

For more than 40 years, research on alternatives to the original oil-film light valve has led to a remarkable diversity of approaches including those based on acousto-optics, elastomers, micromechanical gratings, electro-optics, magneto-optics, liquid crystals, membranes, cantilever beams, piezoelectric mirrors and torsion beams. These technologies have attempted not only to overcome the brightness limitation of the CRT but also, the limitations of size, weight, stability, and cost of the oil-film projector.

With the advent of high-density integrated circuits, the idea of putting a display on a chip became very attractive, but no display technology could be seamlessly integrated onto the chip to take full advantage of this new method of electronic circuit mass production. The semiconductor industry has moved into the digital age, achieving success with

advanced consumer services and products such as digital satellite TV, digital cell phones and digital video discs. Now it is even more attractive to learn how to mass produce displays on silicon and to utilize the fidelity and stability inherent in digital technology.

The DMD is the first display on a chip to be commercialized for projection applications. It is the only all-digital (source to eye) projection display technology on the market. Although LCDs have recently been integrated onto silicon address chips, they are still based on analog technology and subject to its limitations. The modern DMD is nothing less than a spatial light modulator taken to its ideal limit of performance. Functioning as a fast, efficient digital light switch, rather than an analog output valve, it combines the image fidelity and the stability and noise immunity that are inherent and so compelling in other digital technologies.

Early in the 20th century, the CRT provided the first electronic window for seeing beyond the horizon. At the close of the 20th century, Digital Light Processing and the DMD provide the perfect electronic window for seeing into the digital world of education, business, and entertainment (including motion pictures) as well as yet-to-be-charted new forms of multimedia entertainment. Digital Light Processing may well be the ultimate projection display technology for the emerging digital age of the 21st century.

## Acknowledgments

**Trademarks**

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Grating Light Valve and GLV are trademarks of Silicon Light Machines.

Image Light Amplifier and ILA are trademarks of Hughes/JVC.

Teflon is a registered trademark of DuPont.

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**Larry J. Hornbeck**

Larry J. Hornbeck is a TI Fellow in Digital Imaging at Texas Instruments in Dallas. He received his Ph.D. in solid-state physics from Case Western Reserve University in 1974. In 1973, he joined Texas Instruments, where his initial work was to develop charge-coupled device (CCD) image sensors for video and electronic still photography applications. He invented a concept for the first 3-D charge-storage of multiple images within a CCD that became known as the stratified channel CCD.

Larry began the development of analog microelectro-mechanical systems (MEMS) arrays for optical signal processing in 1977. In the early 1980s he expanded his development activities to include printing and projection display applications for optical MEMS arrays. A major milestone was his invention in 1983 of a low-temperature MEMS fabrication process which is compatible with conventional MOS wafer processing.

In 1987 Larry invented the Digital Micromirror Device™ (DMD™) microchip, a MEMS array of fast digital light switches monolithically integrated onto a silicon address circuit. The DMD forms the basis for Texas Instruments Digital Light Processing™ (DLP™) projection display technology. Currently, Texas Instruments is focused on the commercialization of DLP subsystems for mobile, home theater, videowall, and large-venue (high brightness) projection display applications. Following his invention of the DMD, he has continued to refine the technology with numerous contributions that have led to improved performance and reliability. In addition, he invented a DMD-like architecture and fabrication process for an uncooled infrared (IR) image sensor chip having low-cost night vision applications.

Larry has received awards from *Discover Magazine, Aviation Week and Space Technology and PC Magazine.* He was the 1995 recipient of Germany's prestigious Eduard Rhein Foundation Technology Award for the invention of the DMD. The Dallas Fort Worth Intellectual Property Law Association named him the 1997 North Texas Inventor of the Year. That same year he and W. Ed Nelson received the distinguished Rank Prize at the Royal Society of Medicine in London, for the invention of the DMD and for pioneering its use in full color video projection. In 1998 he received an Emmy from the Academy of Television Arts & Sciences for Outstanding Achievement in Engineering Development for the invention of the DMD.

Larry holds twenty-nine patents in CCD, IR image sensor and DMD technology, including the fundamental patent for the Digital Micromirror Device. He is a member of the IEEE, OSA, SID and SPIE. ❏

# Digital Imaging's integrated product development process

*Abstract: The evolution of Digital Imaging (DI) from research and development to a product-oriented organization required additional discipline and focus on business processes. The high-level business map was defined to flow information from the marketplace requirements into the final product delivered to the customer. One of the critical pieces of the process flow was the product development process–translation of market and customer requirements into physical form.*

*The product development process needed to be a dynamic document that met the needs of the organization. It needed to tightly couple the market requirements with the final product and ensure alignment to DI's business strategies. A cross-functional team evaluated processes from inside and outside TI to limit the amount of effort the team would need to expend. The phase-gate process documented by DI covers product life cycle from concept to closeout in seven phases. The gates are business-focused reviews that evaluate progress, the project's value proposition and alignment with DI strategy. The latest improvement activity added details to the early phases, enabled use of Intranet access and increased consistency of product documentation and storage.*

Digital Imaging (DI) began as a technology development program in 1992. The purpose was to find a use for the Digital Micromirror Device™ (DMD™) and develop demonstration products that would attract customers to DI. Since the products were not intended to go into production, little or no attention was paid to business process related to documenting requirements, verifying producibility or validating functionality. When it became evident that DI was a viable business in 1994, teams were established to define a business process model and a product development process.

## DI's business process model

The business process team was not interested in "reinventing the wheel" and began searching for successful existing models applicable to DI's needs. TI's Semiconductor Group (SC) model provided the basic structure for a non-end item product driven by market requirements. The TI calculator model provided the concept of a multi-layered market element. The DI team integrated the two models and released the Digital Imaging business process model in October 1994.

As shown in *Figure 1*, business management and strategy development for DI's products are driven by the needs of the market. The primary market interface is coordinated through the original equipment manufacturer (OEM). Demand assumptions are generated on end-user needs. A product business model and work-share allocation between OEM and DI are established. Integrated product development efforts are coordinated to achieve full realization of market requirements and timely entry into the market. Sales and operations provide planning and support for product manufacturing and order fulfillment. To support product design and build, a materiel team establishes and manages supplier relationships and alliances. DI's core technologies, driven by product strategy, have both evolutionary and revolutionary paths. Technology development is intended to lead product development to lower the risk of new technology insertion into DI's products.

There are several enablers to this business model. Assessment of DI's product quality, reliability and product safety are provided by an independent Quality Reliability Assurance (QRA) organization. Staffing and training of all DIers is handled through division-based Human Resources (HR) services. Legal Support Services manage all intellectual property and contractual issues. Information technology provides computer and tool infrastructure support

## Alice Parry, Bob Stoddard and Ron Barry
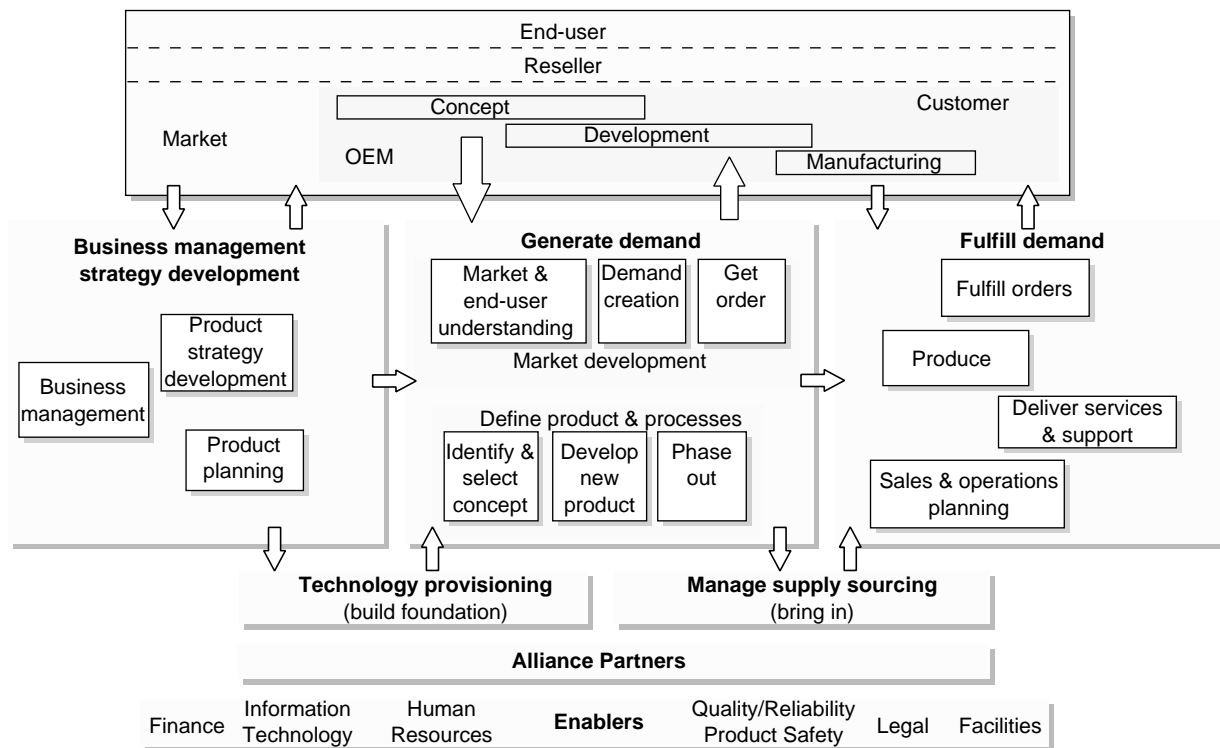
**Figure 1.** Digital Imaging's business process model.

and a networked environment to facilitate information sharing. Finance reports current status and forecasts upward into TI's corporate structure. It also provides support for financial risk assessments at the product level.

## Key business objectives drive process

The business process model made it clear that the product development process must be driven by and aligned with DI business objectives. The product development team used the business model to clarify how development facilitated this flow and to help meet DI's business objectives. With this process the customer is the center of DI's focus.

Customer satisfaction is the primary focus for DI. Part of the satisfaction quotient includes product-related business objectives such as:

• Market driven product requirements
• Meeting customers' needs
• Meeting time-to-market targets
• Reducing product costs
• Reducing product development cycle time
• Improving product quality.

*Figure 2* shows a general information flow between customers and various DI organizational and functional entities.

During the early phases of DI's product development process, Marketing is responsible for identifying customer careabouts and translating them into market requirements. Systems Engineering creates the product specification and design requirements from the market requirements. Target product costs and time-to-market requirements also are established by Marketing.

Proper market and systems analysis are critical to this process. Product Marketing's presence as an integral part of the product development team helps focus the development effort toward these objectives. The product development team, which includes manufacturing, tailors the process to meet the time-to-market window without sacrificing product quality. Product quality and reduction of product costs and cycle time are the responsibility of all functions including engineering, operations and QRA. Concurrent engineering during the requirements and design phases by engineering, manufacturing and customers, help to reduce the amount of rework nec-
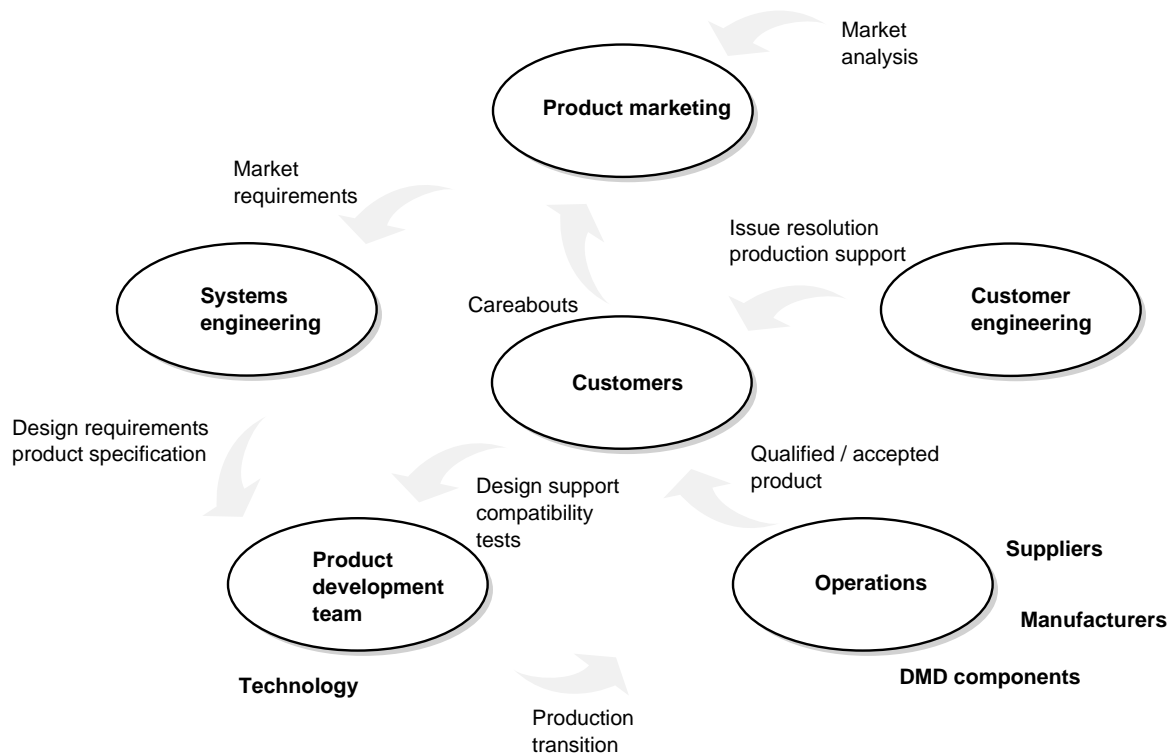
**Figure 2.** Information flow model.

essary as the development moves toward production. Emphasis is placed on design for manufacturability and design-to-cost. The concurrent efforts provide the basis for reducing cycle time and keeping overall product costs in line. Solid design practices, engineering, management and testing activities ensure product quality and customer satisfaction are achieved.

Issues management and production support are important to the customer satisfaction equation. Customer Engineering, within the Marketing organization, is responsible for technical interface with customers to document and resolve problems and complaints.

## DI's business-focused product development process
A cross-functional team was established in 1994 to define a product development process. This team used the approach of reviewing existing processes internal to TI to identify a process appropriate for DI's needs. The highly successful process that was defined by Systems Group to meet government requirements was large and complex and would have been difficult to scale down to meet DI's entre-

preneurial, quick-turn product cycle need. SC's process carefully defined the component development, but did not include the product assembly and customer integration issues that were critical to DI's success. The process used in TI's former Information Technology Group (ITG) was the closest fit for DI's requirements. It was modified to expand beyond the traditional product development life cycle that begins after product specifications are defined *(Figure 3)*. The DI team added detail to document concept definition (Phase 0) and market analysis (Phase 1) that lead to the product specifications and to clarify product phaseout (Phase 7 [not shown]).

## The integrated process flow
Product development is market-driven, integrated and phase-gated. Each phase has a predefined, but tailorable set of tasks followed by a Decision Point Review (DPR). Collaborative multidiscipline teams are established early in the overall process to ensure all aspects of product development, including manufacturing, are addressed during these phases. Marketing drives the first two phases (0 and 1). A business case and high-level market requirements are established and approved. System Engineering ana-

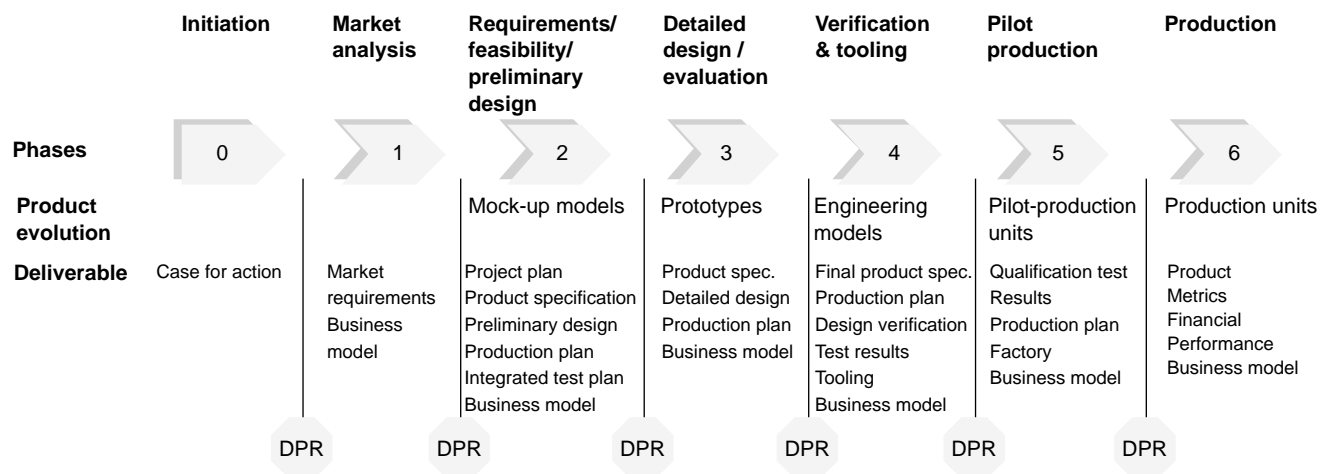| | Initiation | Market analysis | Requirements/ feasibility/ preliminary design | Detailed design / evaluation | Verification & tooling | Pilot production | Production |
|---|---|---|---|---|---|---|---|
| **Phases** | 0 | 1 | 2 | 3 | 4 | 5 | 6 |
| **Product evolution** | | | Mock-up models | Prototypes | Engineering models | Pilot-production units | Production units |
| **Deliverable** | Case for action | Market requirements Business model | Project plan Product specification Preliminary design Production plan Integrated test plan Business model | Product spec. Detailed design Production plan Business model | Final product spec. Production plan Design verification Test results Tooling Business model | Qualification test Results Production plan Factory Business model | Product Metrics Financial Performance Business model |
| | | DPR | DPR | DPR | DPR | DPR | DPR |

**Figure 3.** Phased product development process.

lyzes the market requirements to establish their feasibility and provide an initial assessment of technical risks.

At the beginning of Phase 2, Marketing and Systems Engineering agree to a set of requirements that will drive product design. Systems Engineering continues the trade-off and technical analysis effort to establish architecture and detailed requirements. The detailed requirements are provided to the designers for initial prototyping efforts. A preliminary design is reviewed and mock-up models are built.

The product specification, a contractually binding document between the customer and DI, is initially developed during Phase 2 and finalized before the end of Phase 4. This document describes the expected product performance and is the basis for product qualification.

Activities within Phase 2, such as feasibility studies, trades, risk assessments, test, production planning and development of mock-up models set the stage for a rapid thrust into production. Discontinuance of a product development effort could come as early as Phase 2 if critical business objectives established by Marketing are not met.

In Phase 3, detailed design and evaluation of prototypes begins. Coordination with customer designers, manufacturers and suppliers is critical during this phase.

Engineering models are developed within Phase 4. Design verification tests are executed during this phase to ensure all product requirements are met. Preparation for production including tooling, regulatory compliance certification and build planning

begins in Phase 4. Production readiness reviews are used to ensure that the engineered product is prepared for product manufacturing.

Testing and additional tool refinement continues in Phase 5, Pilot Production. Production begins in Phase 6 and is managed by production engineering. Phase 7 (not shown) is the closeout of a product. This phase entails lifetime buys, inventory planning and closeout communications.

## DI's product development process improvement

In 1997 another team was given the task of updating the DI product development process to incorporate lessons learned and to remove barriers to effective process use. The team held focus group meetings with Engineering and Marketing and searched benchmark databases to identify process improvements.

The team determined that the basic process was adequate. The SC market analysis process was adapted to add detail to activities in Phases 0 and 1. The former Personal Productivity Products division provided the basis for an electronic project notebook in Lotus Notes.™

To simplify use of the process documentation, the team established access and links through the TI Intranet. The current process is an electronic document with a tailoring matrix, document templates that are hot-linked to the project management notebook, an integrated corrective action item system and a "lessons-learned" database. *Figure 4* shows a few pages from the electronic project notebook as seen through TI's Intranet.
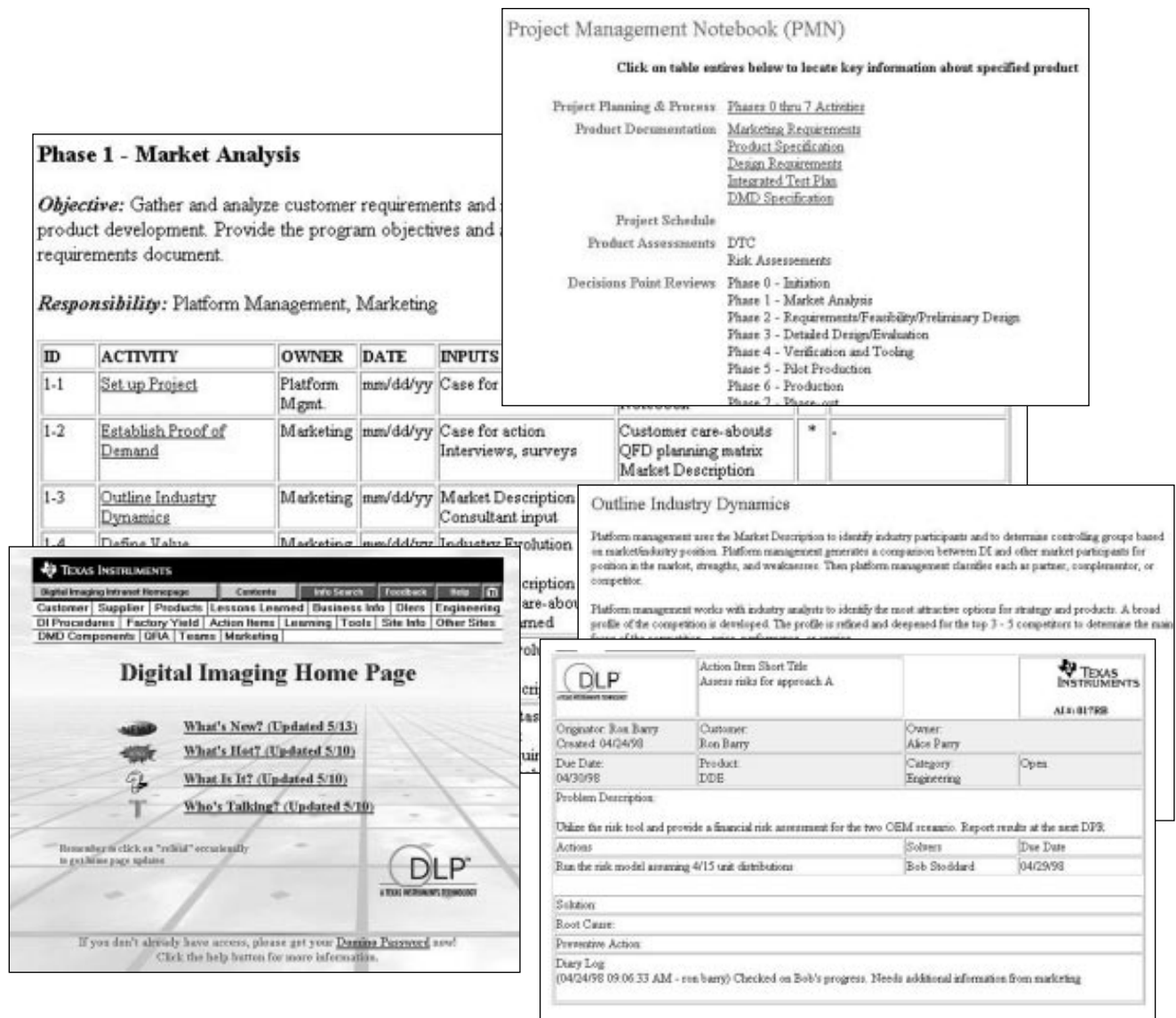
**Figure 4.** Excerpts from electronic project notebook.

## High value aspects of the process

There are five aspects of the DI product development process that provide the greatest value.

**Business focus.** The product development process is focused on generating a product that meets market needs and is aligned with the DI business strategy. Phases 0 and 1 are concentrated on identifying the requirements of the market place. Platform managers have profit and loss responsibilities for a given area of the business and are responsible for these two phases. They are accountable for the product strategy and alignment with DI's business strategy.

The business focus is supported through all seven phases of the product life cycle by the gating process. At the end of each development phase, a decision point review is held. At the review, the business case and technical progress are reevaluated to ensure that the product is consistent with market requirements and business strategies. This process step helps eliminate wasted investment by identifying problems early in the development cycle.

**Risk analysis and modeling.** Risk analysis occurs throughout all product life cycle phases for each project team. The goal is to translate risks into financial impacts on revenue, profit from operations, gross

margin and discounted cumulative cash flow at the Digital Imaging project and platform level. A risk team, including Marketing, Project Management, Systems Engineering and Manufacturing (design-to-cost) is established. The team is responsible for following the risk analysis process shown in *Figure 5*.

Digital Imaging developed a financial risk management tool that leverages information in the traditional financial income statement (such as revenues, gross margin, profit and cash flow) and supports analysis of the combined uncertainty of various factors shown in Figure 5. A member of the DI Finance team facilitates the risk team and coordinates use of the tool and process. Members of the risk team monitor inputs and identify significant changes which trigger updates to the risk analysis.

The results of running the risk tool on "what if" alternatives are compared and presented at the decision point reviews. Business decisions to proceed or stop the development are based, in part, on the analysis. Risk management implemented by an experienced team using the financial risk tool enables the team to manage project risks and identify the impact to the financial bottom line.

**Team based.** A cross-functional development team is established at the end of the market analysis phase. Every attempt is made to move intact teams with domain expertise from project to project. Team members are involved in the activities described in the product development process across all phases (*Figure 6*). Engineering functions, such as producibility, reliability and quality assurance, are active participants in the development teams.

Responsibility for the product begins the transition to production engineering with the kick-off of the production readiness activities in Phase 4 (verification) and completes with the handoff at the end of Phase 5 (pilot production). The use of cross-functional teams throughout the development effort ensures that a quality design enters the factory and that a robust product is delivered to DI's customers.
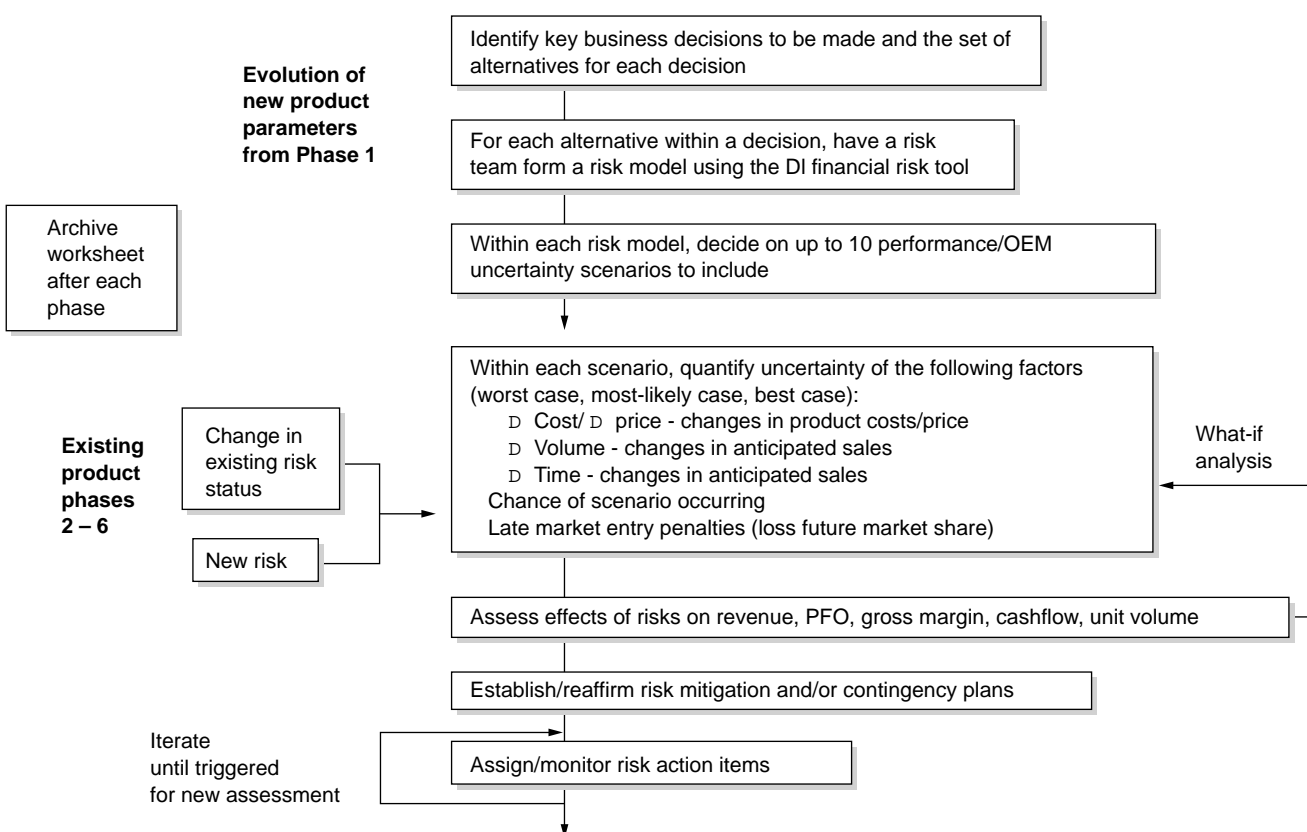
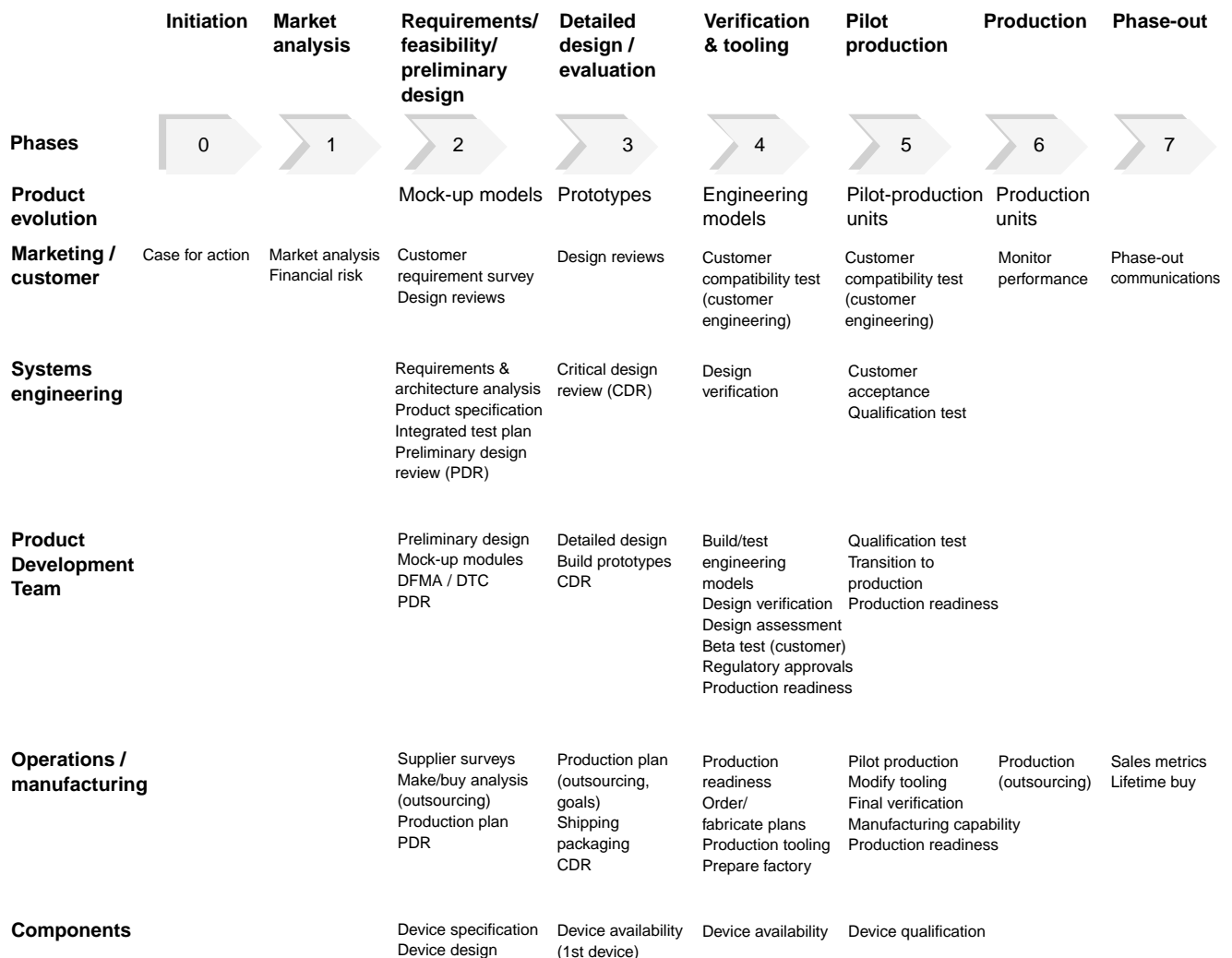Figure 5. DI's risk analysis process.

| | Initiation | Market analysis | Requirements/ feasibility/ preliminary design | Detailed design / evaluation | Verification & tooling | Pilot production | Production | Phase-out |
|---|---|---|---|---|---|---|---|---|
| **Phases** | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| **Product evolution** | | | Mock-up models | Prototypes | Engineering models | Pilot-production units | Production units | |
| **Marketing / customer** | Case for action | Market analysis Financial risk | Customer requirement survey Design reviews | Design reviews | Customer compatibility test (customer engineering) | Customer compatibility test (customer engineering) | Monitor performance | Phase-out communications |
| **Systems engineering** | | | Requirements & architecture analysis Product specification Integrated test plan Preliminary design review (PDR) | Critical design review (CDR) | Design verification | Customer acceptance Qualification test | | |
| **Product Development Team** | | | Preliminary design Mock-up modules DFMA / DTC PDR | Detailed design Build prototypes CDR | Build/test engineering models Design verification Design assessment Beta test (customer) Regulatory approvals Production readiness | Qualification test Transition to production Production readiness | | |
| **Operations / manufacturing** | | | Supplier surveys Make/buy analysis (outsourcing) Production plan PDR | Production plan (outsourcing, goals) Shipping packaging CDR | Production readiness Order/ fabricate plans Production tooling Prepare factory | Pilot production Modify tooling Final verification Manufacturing capability Production readiness | Production (outsourcing) | Sales metrics Lifetime buy |
| **Components** | | | Device specification Device design | Device availability (1st device) | Device availability | Device qualification | | |

**Figure 6.** Cross-function activities during product development.

**Tailoring.** The product development process activities describe a robust generic product development. However, each development effort is unique. The product can vary from an entirely new platform design to a relatively simple upgrade of an existing product. The cross-functional development team needs the flexibility to define a process that specifically addresses their requirements. At the start of Phase 2, the product team uses the high-level requirements (defined in Phases 0 and 1), schedule, financial model and cost goals to evaluate the process activity matrix. Each activity is evaluated for applicability to the project. Tailoring allows the team to select the most cost-effective and value added activities to be performed during the development. The results of the tailoring are one of the major inputs to the planning process.

**Phase synchronization.** In preparation for the decision point review, platform management conducts a "phase synchronization." The phase synchronization has two elements. First, the development team evaluates the past phase and documents lessons learned that address technical, product, market or process issues. The lessons learned are documented in an electronic project notebook. The second element is planning the next phase. The team reviews their tailored process activity matrix and "retailors" the next phase activities, as necessary. The lessons learned database is searched for applicable topics from other projects. The phase synchronization ensures sharing

of lessons learned across project teams and allows the team to replan the project to address significant changes to technical requirements, cost, schedule, change in market conditions, etc.

## Process contribution to business metrics

The product development process definition cannot be an end in itself. The purpose must be to increase Digital Imaging's performance in key business metrics. The business metrics are measurements that provide a barometer for judging DI's performance and setting thresholds for identifying improvement opportunities. Three metrics were selected for engineering and operations focus in 1998.

- **Customer satisfaction.** Measured by six-month customer surveys. The goal is to increase the overall satisfaction by 13% by Fall 1998. An improved and successfully deployed product development process can contribute to customer satisfaction by helping to reduce time to market and increase quality of the products as configured and delivered.
- **Integrated first pass yield.** Measured by factory output. The goal is to improve integrated yield at production release by 20%. The product development process calls out specific activities that directly impact integrated yield.
  - ♦ Clarifying, documenting and negotiating customer and market requirements
  - ♦ Involving customer and critical suppliers as early as possible during design, implementation and test
  - ♦ Initiating production planning (including yield goals) during preliminary design
  - ♦ Planning for all levels of test during requirement allocation
  - ♦ Requiring the use of design guides and formal/informal design reviews
  - ♦ Starting production readiness activities immediately after the critical design review
- **Bull's-eye.** Measured by the percent of projects on schedule. The 1998 goal is to increase project's on time to bull's-eye by 20%. The flexibility of tailoring the product development process allows each project team to focus on specific value added activities. The teams can leverage from the disciplined use of lessons learned documented by previous developments to decrease time spent in recreating methods or in following unprofitable paths.

## The next step

The updated product development process has completed extensive review by functional organizations and has been released for use. Based on the limited deployment and implementation of the previous release, the update team has identified two process goals for 1998.

- Successful and widespread application of the process
- Continuous improvement

The team has identified four approaches, taken from standard concepts of successful change management which will increase the probability of successful process deployment.

- Request sponsorship from the DI Leadership Team to communicate expectations regarding use of the process
- Generate training presentation for all DI employees
- Establish process level metrics integrated with process progress reviews
- Perform selective compliance audits

The goal of continuous improvement will be met by disciplined use of lessons learned and by incorporating information received from compliance audits.

Benchmarking data indicates that companies with well-defined product development and project management processes can have significantly better performance than their competitors:

- Cycle time (40% faster time to market)
- Revenue (25% higher growth)
- Effective use of resources (200% more efficient per dollar invested)

A flexible process that is tightly coupled to customer and market requirements will help propel high quality Digital Imaging products into the marketplace earlier than the competition—yielding benefits in revenue, growth, customer satisfaction and shareholder value.

**Trademarks**
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Alice Parry is the Process Development and Configuration manager in the Digital Imaging Quality and Reliability Assurance organization. She has been in DI since 1993 and set up software and hardware configuration management systems. She was a member of the teams that established the business process model and the product development process. She is a member of the software and systems engineering process improvement teams and is currently formulating a configuration management solution in SAP.

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Prior to her DI assignment Alice spent 14 years working with TI's former Systems Group (now Raytheon Systems Company) in configuration management and software quality. She has been active in the TI software process improvement effort (SofTware Engineering Process and Software Core Competency Teams) for six years.

As a member of the Dallas Business and Professional Women's organization, Alice taught the Leadership Skills and Development class. She views her experience and personal networks as strengths that have enabled her to identify and select best practices from defense and commercial communities.



**Bob Stoddard**

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Bob is an active member of the IEEE and the American Society for Quality and is the program chair and deputy chair of the Dallas/Fort Worth Software Process Improvement Network (SPIN)—known locally as the Association for Software Engineering Excellence (ASEE). Bob holds ASQ certifications in reliability, quality, software quality and auditing.



**Ron Barry**

Ron Barry is currently the engineering manager within DI's Systems, Engineering and Operations organization. He is responsible for the development and improvement of engineering processes for software, electronics and systems engineering. Ron is the lead facilitator of the teams supporting each of these disciplines. He also is the facilitator of the Risk Management, Test, Design-to-Cost and Intranet teams. Ron coordinates staffing activities and engineering tool evaluation and acquisitions. He is a member of DI's People Development Team and assists in the coordination of specialized learning development coursework. He is also a member of DI's Technical Council and TI's Technical Communications Committee.

Ron is a Senior Member, Technical Staff and a Technical Award for Excellence recipient from TI's former Systems Group. He joined TI in 1979 after receiving his master's degree in computer science at West Virginia University. Prior to DI, Ron served in both the Systems and Industrial Automation Groups. ❏

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# From ICs To DMD™s

*Abstract: This article describes the process of the DMD™ and how it compares to standard IC and MEMS processing. The processes and device architecture will be described from CMOS through assembly test. A key goal for this device is to have similar processes and processing equipment as in the semiconductor industry. Packaging and electro-optical testing are two areas where this device does not follow mainstream IC components. The complete process flow, including package assembly and test are performed in a cleanroom environment due to the particle sensitivity of this mechanical device. Our lowest and highest resolution products in production have more than one-half and one million moving elements, respectively. Today, the majority of units we ship are defect free. The DMD has demonstrated capability of meeting customer performance and reliability expectations. Our technology and manufacturing capability can support current resolution and future, higher resolution products.*

Over 40 years ago bulky vacuum tubes and wires made up the piece-by-piece assembly of electronics. The invention of the transistor and the integrated circuit began a technological revolution—the miniaturization of electronics. Mechanics is now poised on the verge of similar revolution with its own miniaturization.[1] The driving force for the miniaturization of mechanical systems is cost, size, speed, weight and precision, while providing an effective interface between the macro and the microdynamic world. The terminology for these small mechanical systems is microelectrical mechanical systems (MEMS).

The majority of MEMS products being produced today are targeted to replace existing products. Replacement alone, however, is not sufficient—the new device must provide more functions with better performance at a reduced cost. Silicon gas chromatographs, mass flow sensors, tactile sensors, optical fiber alignment guides, pressure sensors (automobile, medical, and industrial), electrostatically driven micromotors, microactuators, chemical microsensors, microtubing and microvalving are just a few examples of miniaturized mechanical systems.[2,3] The Digital Micromirror Device™ (DMD) is a MEMS device that uses the miniaturization advantages of both IC and mechanical systems.

Fabrication of the DMD comprises several major operations. These include SRAM CMOS circuitry, DMD superstructure (i.e., the structure built on top of the CMOS) fabrication, window assembly fabrication,

packaged component assembly and device test and characterization. To build the DMD, a broad spectrum of technologies, including semiconductor, packaging, optics, materials and test expertise, were brought together.[4]

The DMD is a reflective, passive, spatial light modulator composed of an array of rotatable aluminum mirrors currently targeted for the projection displays market. It offers performance far exceeding liquid crystal display (LCD) and cathode ray tube (CRT) projection display technologies. *Figure 1* illustrates the micromirror element, which is compromised of an aluminum mirror suspended over an air gap by two thin, post-supported, mechanically compliant torsion hinges that permit a mirror rotation of ±10°. As a digital light switch, the DMD operates
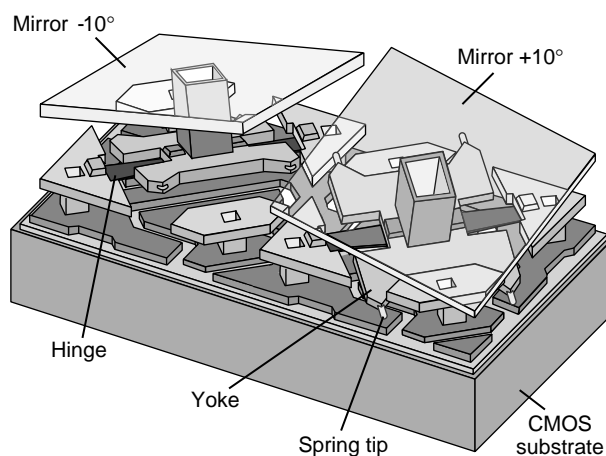


**Figure 1.** DMD pixel (transparent mirror, rotated).

## Michael A. Mignardi

under dark field projection optics to direct light from a projection source into or out of the pupil of a projection lens (*Figure 2*).

Unlike most MEMS devices, the DMD is fully integrated and monolithically fabricated on a mature SRAM CMOS address circuitry. The drive circuitry for most MEMS devices is either off-chip or on the chip but outside the active mechanical element region.

The birth of this technology occurred within TI's Central Research Laboratories under the direction of Larry Hornbeck (the inventor), Ed Nelson and Jeffrey Sampsell. The ability to transfer this technology into a high reliability, yielding- and performance-based product was not realized until the formation of the Digital Imaging business.

The immense level of development and production effort to fabricate the DMD is equally divided into thirds: the DMD superstructure, package assembly and electro-optical test. Although the tangible product produced in Texas Instruments is the DMD itself, of interest to our end customer is the projected image with optical performance being the most critical metric.
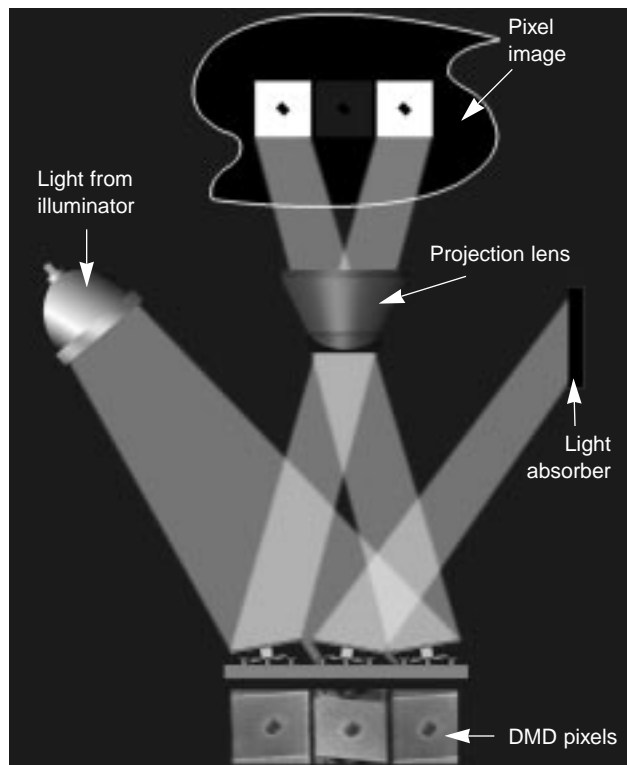


**Figure 2.** Dark field projection of a DMD.

A major goal set during the early days of Digital Imaging was to fabricate this technology using standard semiconductor processes and equipment tools as a means of efficient asset utilization. In keeping this goal, in February of this year we transferred the wafer portion of the processing to the DMOS-IV fabrication facility. This truly demonstrates the ability for this technology to be fabricated in a mature wafer fab using similar semiconductor processes and equipment tools.

The DMD is currently in volume production for SVGA (super video graphics adapter, 848 x 600 pixels) and XGA (extended graphics adapter, 1024 x 768 pixels) resolution display formats. It is a high performance display device that can be manufactured with high yield at marketable cost.[5] This publication provides an overview of key details of the development and production effort of the DMD manufacturing process and how it compares to the integrated circuit (IC) industry as well as other MEMS components.

## CMOS fabrication

The DMD mechanical element (commonly referred as a "pixel", for picture element, or "mirror") is processed over the CMOS architecture. Our CMOS is processed in DMOS-IV and consists of conventional SRAM cells. The SRAM underlying each mirror is a six-transistor circuit or storage cell fabricated using a twin-well CMOS, 0.8 μm, double-level metallization process. *Figure 3* shows the layout of the integrated DMD structure. The SRAM cell provides addressability to each individual mirror. The mirror for each device is 16 μm square on a pitch of 17 μm. The size of the mirror is determined by both the optical system and the minimum geometry achievable for the CMOS SRAM cell.

Once the double-level metallization is complete, a final interlevel dielectric is applied. This dielectric level is the surface on which the DMD pixel architecture is fabricated. It is critical that this level is locally flat. That is, differences in topography as little as 800 angstroms across the landing surface of a pixel can negatively impact the projected image in certain systems. The human eye is extremely sensitive to very low contrast changes. For this reason, chemical-mechanical polishing (CMP) is required for adequate planarization. Once CMP is complete, vias are generated in the dielectric. For each pixel there is a pair of address electrodes connected to the complementary sides of the underlying SRAM cell (Figure 3). Each pixel has two vias within the cell. Depending on the
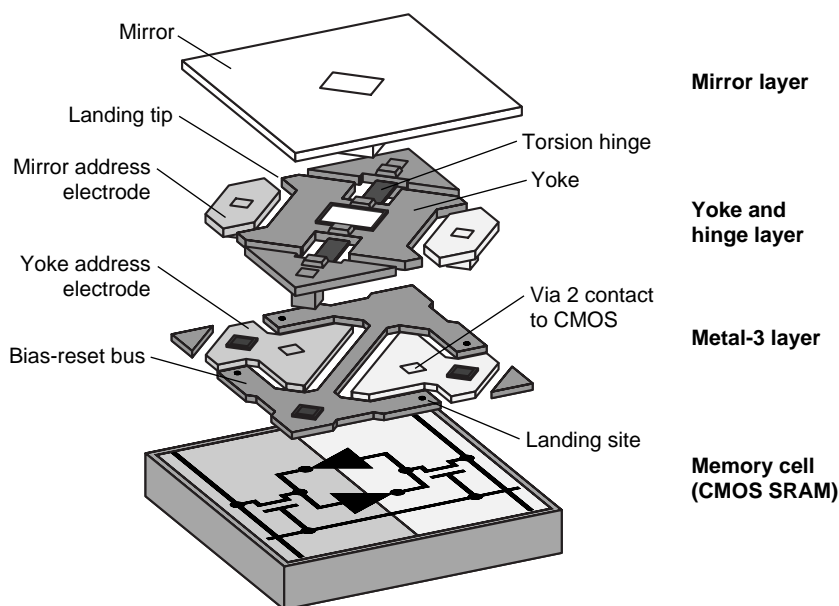
Mirror

Landing tip

Mirror address electrode

Yoke address electrode

Bias-reset bus

Torsion hinge

Yoke

Via 2 contact to CMOS

Landing site

**Mirror layer**

**Yoke and hinge layer**

**Metal-3 layer**

**Memory cell (CMOS SRAM)**

**Figure 3.** DMD pixel electrical schematic.

SRAM state, a combination of bias and address voltages electrostatically attracts each pixel element to one of the two address electrodes. One address side represents the "off-state" while the other side represents the "on-state" of the pixel.

## Superstructure fabrication

IC fabrication employs surface micromachining layering techniques involving repetitive deposition, pattern and removal processes.[6] The DMD as well as many MEMS components use surface micromachining layering techniques. Other MEMS components can be fabricated using bulk micromachining, bonding or high-aspect ratio (or LIGA, Lithografie, Galvanik, Abformung) techniques.[7] Six metal layers make up an entire pixel cell—two metal layers of the CMOS SRAM cell and four additional metal layers that define the pixel superstructure. *Figure 4* provides a simplified process flow of the superstructure, test and assembly operations.

An attractive feature realized in the processing of the DMD superstructure is its outgrowth from the IC industry and its fabrication sequence. Many of the processes and equipment tools used in the superstructure fabrication (or front-end) are common with the semiconductor industry.

After contact openings (i.e., the vias) the address circuit electrode is formed on top of the CMOS dielectric layer. The aluminum address electrode film is sputter-deposited onto the dielectric, lithographically patterned and plasma etched. An organic sacrificial planarizing layer is then spun over the electrode and patterned with vias, which subsequently forms the support posts. These posts provide not only mechanical support but also serve as electrical contacts.

Two proprietary metal alloy layers are employed for the buried hinge process. The hinge alloy is sputtered on top of the sacrificial layer, followed by a plasma-deposited masking oxide that is patterned to define the hinges. A typical semiconductor metal deposition occurs on an inorganic dielectric (e.g., $SiO_2$) rather than an organic dielectric as is done with the DMD. Deposition of a second alloy layer buries the hinge oxide and forms the beam. This, in turn, is followed by still another plasma-deposited masking oxide, which is patterned to form the beam. A single metal plasma-etching step forms the hinges and beam. The support posts consist of both the hinge and beam metals. Standard IC technology tightly controls the critical dimensions in both x and y directions. However, the z-axis dimension (i.e., thickness) must also be tightly controlled. Both sacrificial layer and hinge thickness tolerances are precisely controlled to achieve reproducible, uniform mirror tilt angles and addressing voltages, respectively.

A second sacrificial planarizing layer is spun over this hinge-beam level with the process essentially repeated. In this second layer, only one metal layer is deposited—a highly reflective aluminum mirror
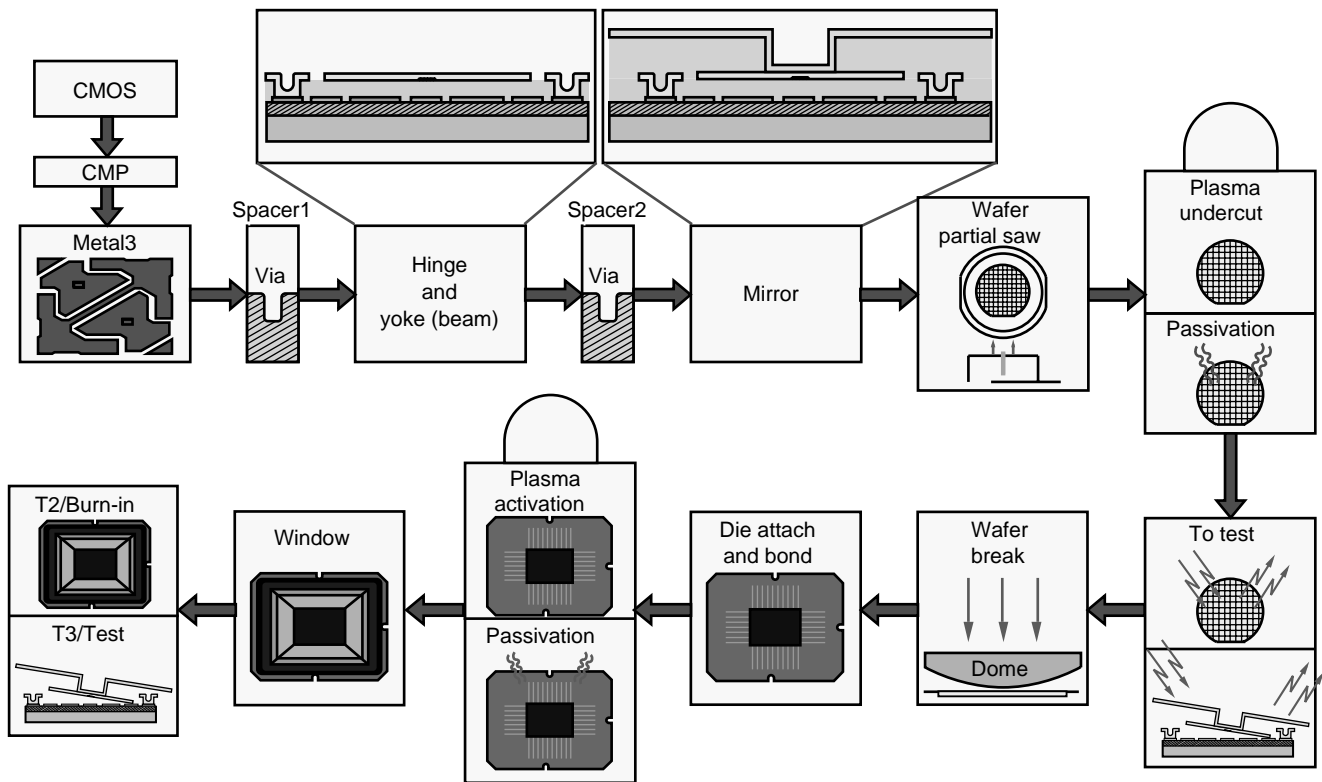
**Figure 4.** DMD process flow.

level. The completed superstructure is called the "hidden hinge" since the hinge is literally hidden by the mirror. This hidden hinge structure is Digital Imaging's fourth generation design. The impetus for this new design was driven mainly by performance requirements to improve the optical efficiency of the device. Figure 1 depicts an exploded view of the pixel.

At this point of DMD fabrication, the superstructure process is complete. This is essentially the demarcation between the front end and back end of the process. The individual pixels, however, have not been released, so mechanical motion of the pixels is not yet possible.

Particle control throughout the superstructure process is critical. Besides causing electrical failures, particles can also cause mechanical failure of the pixel itself. A defective pixel is typically visible on a projected image. Since the DMD is a three-dimensional component with mechanical movement, particle control involves both intralevel and interlevel monitoring. The smallest spacing at the intralevel is on the order of 1 μm. However, the interlevel gap can

approach spacings as small as 0.2 μm during mechanical operation of the DMD pixel. For this reason, particle control well into the submicron range is critical. Our equipment and process engineering teams have done a superb job in achieving defect density levels that are unprecedented in the semiconductor industry. Similar to IC design, development activities are under way to make the DMD architecture less sensitive to these submicron particles.

## Die separation and pixel release

Die separation is typically the first step where the MEMS industry (and the DMD technology) deviates from that of the IC industry. For silicon-wafer applications, the IC industry can employ three die separation techniques, which include laser scribing, diamond scribing and diamond-wheel sawing.[8] Sawing is the common die separation technique. Due to the expense of most MEMS packages, it is imperative that only functional devices meeting our specifications are assembled. Therefore, the MEMS mechanical element must be released for functionality testing prior to assembly. As with any high volume process,

batch or single wafer processing is the preferred manufacturing strategy. Processing individual die is typically a time-consuming and labor-intensive process—even with established automation tools. The separation of DMD die on a silicon wafer and subsequent packaging of those die was a significant core challenge for the DMD program.[4]

The DMD manufacturing strategy is to release all pixels at the wafer level rather than the individual die level (as was initially done in TI's Central Research Laboratories and the early days of Digital Imaging). It is not feasible to first release the DMD pixels and then saw the wafer. The amount of water flow through the saw would destroy the superstructure. Instead, a protective layer is placed on top of the mirror level, followed by the wafer being partially sawn and then cleaned to remove saw debris. The release process involves an organic isotropic ash process that removes both sacrificial layers from the DMD pixel using a single wafer asher. An air gap has now been created under the mirror. These steps, including the saw process, occur within the Class 10 (less than ten 0.3 μm particles per cubic foot of air) cleanroom environment. The wafer can now be presented to the wafer tester as described below.

Once wafer level test is complete, separation of the functional die from the wafer is the next crucial process step. TI has a proprietary process that breaks the wafer along the partially sawn scribe kerfs (Figure 4). This process must also be an extremely clean process since any silicon debris generated during the break process can cause mechanical failure to the pixel. Similar to standard sawing of IC components, the separated die remain on saw frames (with dicing tape) so the entire wafer can be presented and processed on a die attach assembly tool.

## Package assembly

Most MEMS technologies consider packaging as their Achilles heel of manufacturing.[6] The DMD package is an integral part of the DMD. The package not only provides signal and power lead connections to the chip, but also provides protection from external environments and is a critical component in the optics system. The DMD package is application specific, which is true for most MEMS packages as well. Again, the manufacturing strategy for DMD assembly is to harmonize with standard SC equipment. The DMD, however, cannot rely on conventional packaging technology. Within the MEMS industry (and unlike the IC industry) there is no MEMS packaging infrastructure, accumulated MEMS experience base or significant MEMS depository of assembly knowledge.

Due to the application specific nature of the DMD package, the optical lid for the DMD had to be designed by the packaging development team. Requirements for the optical lid include minimal light losses, optical flatness/parallelism, an optical aperture and a frame to support package welding (*Figure 5*). The window was first fabricated at TI's Defense Systems and Electronics Group. Attached to the internal region of the optical lid is a getter to control contaminants (including moisture). Stiction mitigation is the primary driver for the inclusion of the getter: Moisture (i.e., capillary attraction) can cause the pixel to stick upon landing.
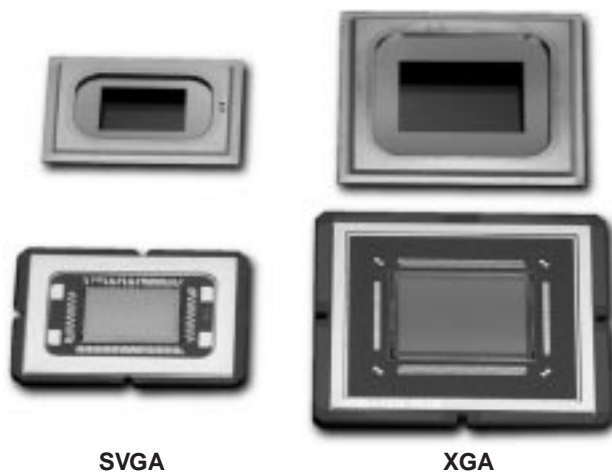


| SVGA | XGA |

**Figure 5.** DMD ceramic headers and lids.

Most IC assembly areas are performed in non-cleanroom environments. Since the DMD pixels are exposed to ambient conditions prior to lid attachment, the entire assembly process is performed in our Class 10 cleanroom. Once the optical lid is hermetically sealed by seam welding to the DMD package, the device can be removed from the cleanroom environment after it is helium leak checked.[4] Although an IC-familiar sequence of assembly operations (i.e., die attach, wire bond, window seal and final test) is employed for the DMD, the product nevertheless requires special handling. Most assembly equipment has been modified to function within a cleanroom environment. Front-side, pick-and-place contact collets were carefully designed so as not to damage the DMD pixels. Die attach adhesives were chosen with low outgassing, low cure temperature and thermal

conductivity qualities—mirror stiction, mirror planarity and hinge compliance are the main image quality concerns, respectively.

Particulate control is a top effort in the assembly area. Scrapping a DMD due to particle contamination at this stage in the process flow is very costly. *Figure 6* shows an example of particulate contamination and its potential effect on mirror functionality. All packaging machines are commercially available semiconductor tools, but each has been modified for low particulate operation. In addition, a proprietary cleaning processes has been developed. Like the wafer portion of a semiconductor process, cleaning steps are used in the assembly process. A process has been developed to clean the device of particle contamination at the package level without damaging the released pixels.[4]
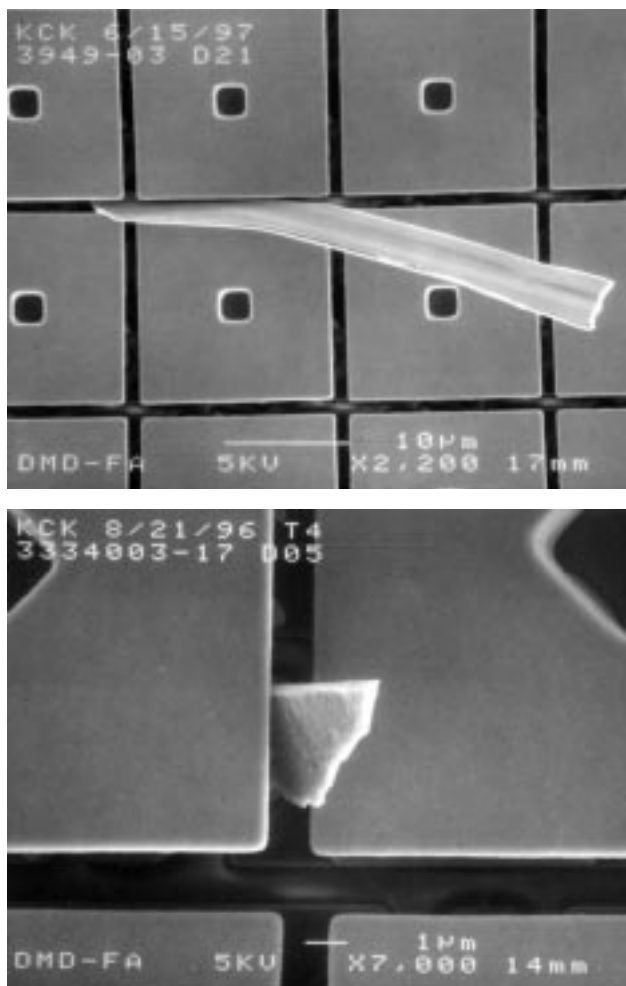


**Figure 6.** DMD pixels with particle defects.

As with any mechanical system, friction is a chief concern. Since the DMD is a mechanical component and the DMD pixels make surface contact, yet another TI proprietary process was developed to mitigate pixel stiction. This process is performed at the package level just prior to placement of the optical lid. During the early stage of DMD development, stiction was a primary focus. The DMD pixel must land millions of times over the life of the product.

Other MEMS products do not make surface contact or the surface contact is very limited during the life of the product. For instance, one accelerometer design, a MEMS component that is used as a sensor for automotive air bag systems, is a component that does not make surface contact during use. Accelerometers, however, are sensitive to stiction during shipping and handling. With a number of key process and design improvements, we have overcome the stiction hurdle.

Similar to processing equipment, the individual package piece parts must also be particle free. For instance, a mechanical and/or electrical failure occurs if a loose particle on the optical lid falls onto an active DMD pixel. A particle that is not loose on the optical lid can still cause a projection system defect. In this case, an optical lid defect can cast a low contrast defect (e.g., a shadow) on the projection screen. To avoid this, special handling and attention to particle control is placed upon processing of the optical lid.

As is typical with most MEMS devices, a significant portion of the total device cost is in the package. In the semiconductor industry the die dominates the cost of the component; however, for the DMD, the package dominates the cost. The biggest challenge for the DMD package development team is to develop a low-cost package that is more in line with what is typical in the IC industry while still meeting our system level optical quality goals and specific device requirements. Likewise, a huge effort is currently underway within the MEMS community to identify low cost hermetic packages that can be used for a large number of MEMS components.

## Wafer, package and projection level testing

Mature parametric test structures are used on production IC components to monitor the health of the semiconductor process. Such parametric test structures have yet to be developed, characterized and implemented for most MEMS components.[6] The DMD does use standard CMOS test parametric structures for electrical characterization such as resistance

and capacitance. Mechanical parametric test structures are not yet established to monitor such things as residual stress of deposited films. Currently, the DMD pixel itself is our best parametric monitor.

Since released pixels are very sensitive to particles, the DMD probe area must remain in a cleanroom environment (typical IC wafer probe areas are outside of this environment). Like any IC component, there are a number of wafer-probing tools commercially available to perform electrical testing. The DMD, however, requires electrical, mechanical and optical testing. The SRAM CMOS functionality can certainly be tested on most electrical testers. The read-write function of the SRAM, however, does not guarantee that pixels are operational. Each pixel must be tested for its opto-mechanical functionality.

Herein lies a major challenge—electrical opto-mechanical testers are not off-the-shelf tools. This challenge is similar to many MEMS products—the tester needs to be somewhat application specific. The DMD test development group did an exemplary job building a low-cost, high-speed, low-particle-generating test set that performs our SRAM CMOS evaluations while also determining the functional state of each mirror on a device. For a typical SVGA product, the tester determines the functionality for over one half million pixels per device. The tester output indicates the number of single bit fails in the SRAM circuitry as well as the pixel array thus determining which die are selected for assembly. This test output also provides process engineering with valuable mechanical parametric information—hinge compliance and mirror stiction in particular.

After package assembly is complete, the device is ready for a mechanical burn-in and final package test. The intent of burn-in is to mechanically stress each pixel to uncover any process problems related to stiction mitigation and hinge deposition. Besides testing for similar characteristics as mentioned during the wafer level test, pixel reflectivity, contrast ratio and tilt angle are also measured. Again, valuable mechanical parametric information is provided to product and process engineering. A projector test is the final test performed prior to shipment. This test uncovers problems that are mostly related to the optical lid such as blemish and border problems. As with any IC test area, the DMD test group has a continous effort in test time reduction.

## Device reliability

Eliminating defective pixels is currently our main device quality objective. DMD reliability means having all pixels remain functional over time, while ensuring each device works over a wide range of operating conditions. The DMD product could not solely depend on U.S. Department of Defense Military Specification reliability standards as used in the IC industry. A number of specialized reliability tests had to be developed to identify failure causes and validate the effectiveness of corrective actions. As with most MEMS devices, reliability tests are application specific. To date we have identified and eliminated all life-limiting failure modes. Future failure rate improvements will result from continued particle reduction efforts currently underway.

## Summary

Having a rich collection of core competencies of CMOS, DMD, window and projector engine fabrication in close proximity has allowed very rapid product development and maturation. The DMD is currently in volume production for both SVGA and XGA display formats. It is highly unlikely that the remaining specialized (i.e., one-of-a-kind) DMD processing equipment will significantly influence any semiconductor equipment manufacturers. Therefore, it is Digital Imaging's responsibility to continue developing processes that are within the mainstream of the IC industry. Compared to other high volume MEMS companies, we are producing a more complex device. For instance, we produce more moving elements on one DMD wafer than most high volume MEMS manufacturers produce in a year.

Our manufacturing team has continually demonstrated increased shipping rates each month to meet rising business needs for Digital Imaging. A very significant percentage of SVGA and XGA devices we ship today are defect free. The demonstrated ability to transfer this technology to a mature wafer fab like DMOS-IV clearly meets our business and technology objectives as we align ourselves with the semiconductor industry. This transfer further enables our business strategy by avoiding a capacity limited situation. We have the technology and manufacturing capability to fabricate devices configured for other applications, including higher resolution (SXGA— 1280 x 1024) displays, currently in initial production. The DMD is meeting our customer performance and reliability expectations as well as our business yield and cost goals.

**Trademarks**

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Michael joined TI and the DMD group when it still
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bilities at that time were process integration and develop-
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world.

He holds a B.S. and a Ph.D. in chemistry from the
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related to DMD processing.

Outside of work, Michael enjoys spending time with his
wife, Marcy, and two children, Landon and Lauren. He also
enjoys any activity or sport that involves being outdoors.