DMD reliability: a MEMS success story

Michael R. Douglass
Texas Instruments, P. O. Box 869305, MS 8477, Plano, Texas 75086
214/567-6774; 214/567-5454 (fax); e-mail: m-douglass@ti.com

ABSTRACT

The Digital Micromirror Device (DMD) developed by Texas Instruments (TI) has made tremendous progress in both performance and reliability since it was first invented in 1987. From the first working concept of a bistable mirror, the DMD is now providing high-brightness, high-contrast, and high-reliability in over 1,500,000 projectors using Digital Light Processing ™ technology. In early 2000, TI introduced the first DMD chip with a smaller mirror (14-micron pitch versus 17-micron pitch). This allowed a greater number of high-resolution DMD chips per wafer, thus providing an increased output capacity as well as the flexibility to use existing package designs. By using existing package designs, subsequent DMDs cost less as well as met our customers' demand for faster time to market.

In recent years, the DMD achieved the status of being a commercially successful MEMS device. It reached this status by the efforts of hundreds of individuals working toward a common goal over many years. Neither textbooks nor design guidelines existed at the time. There was little infrastructure in place to support such a large endeavor. The knowledge we gained through our characterization and testing was all we had available to us through the first few years of development. Reliability was only a goal in 1992 when production development activity started; a goal that many throughout the industry and even within Texas Instruments doubted the DMD could achieve. The results presented in this paper demonstrate that we succeeded by exceeding the reliability goals.

Keywords: DLP™, DMD, MEMS, testing, characterization, reliability, picture reliability

1. INTRODUCTION

The Texas Instruments DMD has achieved a performance level that in some cases exceeded its reliability goals. For every new DMD as well as for each major design change, Texas Instruments performs a detailed failure modes and effects analysis (FMEA). This process assures that all subsequent designs achieve the same high standards for reliability and performance.

Because of the testing and characterization efforts expended since 1992, projectors based on DLP™ technology demonstrate reliability and lifetime superior to competitive technologies. A lifetime estimate of over 100,000 operating hours with no degradation in image quality is the norm. As evidence, the TI reliability department performs ongoing life tests of both DLP™ subsystems and DMD chips. Large screen televisions continue to operate in the lab for over 10,000 hours with no defects and no image artifacts. Small, portable, and lightweight conference room projectors operated in our reliability lab for over 26,000 hours with no added defects or image degradation. Nine (9) DMDs, placed on test in December 1995, operated for over 56,500 hours and over $3x10^{12}$ (trillion) mirror cycles (the equivalent of over 100 years of typical office projector applications) with no added defects. These demonstrated results, paired with modeling predictions, support the conclusion that the DMD is exceptionally robust and reliable. For example:

- DMD MTBF > 650,000 hours
- DMD lifetime > 100,000 hours
- Hinge lifetime > $3x10^{12}$ mirror cycles (equivalent to >120,000 operating hours)
- Environmentally robust

This paper will highlight some of the DMD-specific metrology, including, characterization tests (normal, accelerated, and environmental), unique DMD life tests, test equipment development, packaging, modeling and failure analysis. The paper will also discuss how characterization tests are essential to achieving our reliability goals.

2. SETTING AGGRESSIVE, ATTAINABLE GOALS

> If you don't know where you're going, you may not like where you end up.

Texas Instruments invented the DMD in 1987. The concept was refined through the next few years and entered full-scale product development in early 1992[1]. At the time, Texas Instruments anticipated that the DMD provided superior image quality due to its digital operation and reflective approach to modulating light. Unknown was how long the DMD maintained its image quality and how long it operated before failing. The first commercially produced DMD consisted of 840 micromirrors in a linear array. Its application was in a low-resolution printer. Numerous other potential applications existed for the DMD, ranging from printers to high-definition TVs to telecommunications to movie projectors. Understanding each market's unique needs and aligning our goals to satisfy these needs was step one on the road to developing reliability. Every market being considered by Texas Instruments had reliability as a priority. In order to enter each market, this concern for reliability had to be addressed. Some of the earliest applications required only 5000 hours but at high temperatures. Although at the time DMDs could only function for about 100 hours at 65^{o}C before failing, we established what appeared to be the very aggressive goal of 5000 hours at the maximum operating temperature of 65^{o}C. As an organization, we agreed that we would not start shipping products until we achieved this minimum goal. All teams associated with DMD development focussed on achieving this goal.

In addition to the minimum goal, the product development team understood that future markets, such as home theater, consumer television, business projectors, and telecommunications, had much higher expectations for reliability and life time. Therefore, a secondary goal was to assure the DMD was capable of supporting these applications where lifetimes of 50,000 to 100,000 hours would be considered more typical. If the DMD were to achieve these two goals, not only would it meet the market needs but also it would provide another point of differentiation to competing technologies. Texas Instruments wanted DLP™ technology to earn the reputation as the high-reliability technology of choice.

3. IDENTIFY POTENTIAL RISK AREAS

> You need to find problems before they become problems.

There were many theories about how the DMD worked, but actual experience in a production environment was very limited. Some DMDs worked well while others did not work at all. There were obvious process variations and design marginality influencing device performance and reliability. We needed to understand these variations and their effects on the product. Where does one start? Texas Instruments chose to use a Failure Modes and Effects Analysis (FMEA) approach. Experts from various disciplines came together to brainstorm possible failure modes. The group considered process techniques, design constraints, equipment limitations, packaging concerns, test issues, and many other potential failure mode contributors. For each failure mode identified, we documented the potential failure mechanism, when the failure would occur, possible accelerators of the mechanism, the risk to lifetime or failures, and which test or analysis method would be used for verification.

The FMEA approach always starts with a detailed review of the design and process. Figure 1 shows the basic DMD architecture. An actual Scanning Electron Microscope (SEM) image is shown in Figure 2. Although the mirror design evaluated in 1992 differs greatly from the present design shown in Figures 1 and 2, the FMEA concept is the same. Development engineers perform an FMEA on all new DMD designs. This step is critical to rapid development of new designs. Successful application of the FMEA approach has enabled faster time to market with lower risk of failures. It also provides structure to the subsequent development process by identifying the need for test equipment and process development before starting actual tests. By highlighting high-risk areas, the development team has been able to avoid problems that would otherwise have contributed to longer development times and risk to our customers.

This phase of product development relies heavily on design analysis. For new technologies, such as was the case with the DMD, there were many theories but little practical experience. We needed to build our database of experience through a series of methodical characterization tests.

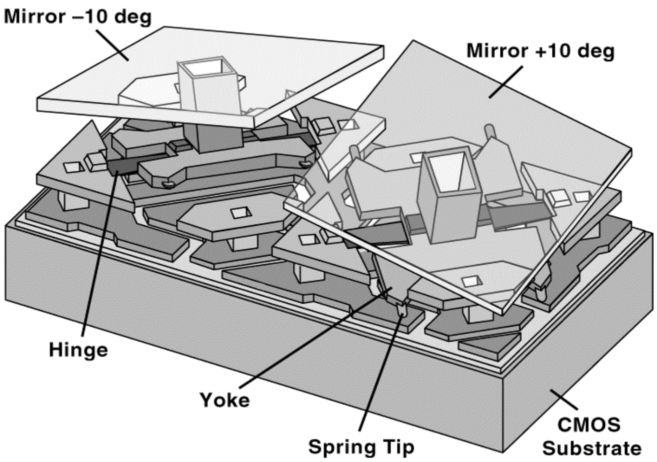

Figure 1 - Illustration of 2 landed DMD mirrors.

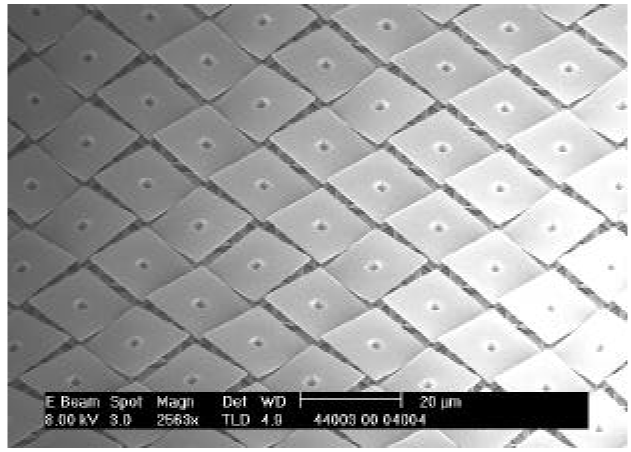

Figure 2 - Top down view of landed mirrors.

4. CHARACTERIZATION AND TEST

> The only bad test is a test where you don't learn anything.

It is actually quite difficult to understand how something works without first knowing how it fails. With this in mind, Texas Instruments implemented a test-to-failure approach. We followed a regimen of postulating potential problems followed by stressful testing to probe and explore the limits of the DMD. Figure 3 represents the concept in a graphical format.

The approach mandates that we perform tests at stresses beyond product specifications. It can apply to various stress types such as temperature, voltage, mechanical (number of mirror landings, mirror duty cycle), chemical, or light. For the DMD, we tested all of these stresses in an attempt to identify potential weaknesses. As the tests identified weaknesses, a team evaluated the results to determine if the test stress was well beyond the needed stress or if design/process changes were necessary. In addition, if we determined that the design/process could be readily implemented, in many cases the team decided to make the change anyway. These decisions resulted in further improvements to DMD robustness. This resulted in large margins and provided flexibility for tradeoffs during future development activities.

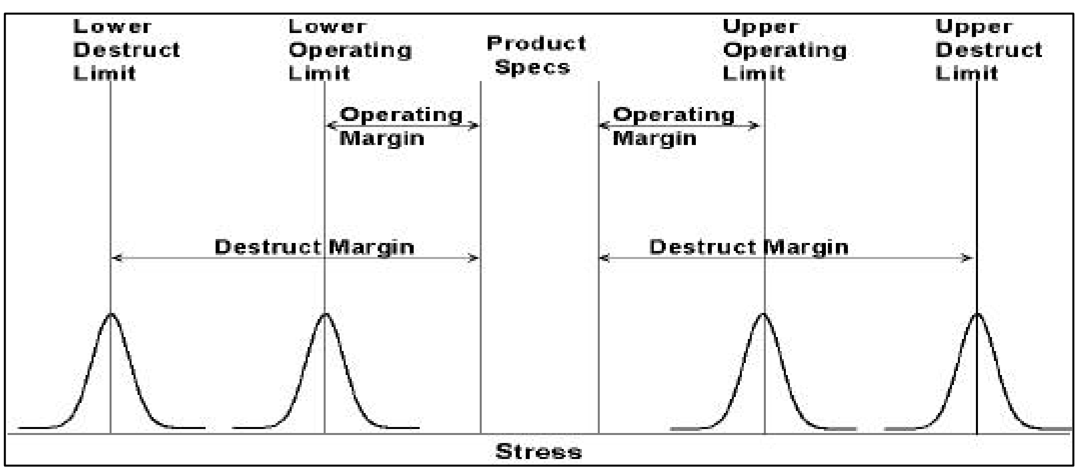

Figure 3 - Accelerated Stress Testing or Test-to-Failure Approach.

The challenge in 1992 was that test capability was extremely limited. As one can imagine, off-the-shelf optical MEMS testers did not exist. TI needed to develop (or highly modify) nearly every piece of in-house test equipment. As with most MEMS devices, we knew that we needed to measure mechanical movement. For the DMD, we provide an electrical and optical input and read an optical output. Early tests used rudimentary equipment incorporating eye loops, microscopes, a stack of power supplies, and human inspection. In spite of the limited capability of these early tests, we learned how mirrors operated under different conditions with different operating waveforms and over a range of temperatures. This knowledge not only helped find problems and eliminate them, but also drove the definition of next-generation test equipment.

Eventually, DMD test equipment matured into a fully automated visual inspection system shown in Figure 4. The test system incorporates an X/Y/theta stage, a CCD camera, optics, and a computer dedicated to interpreting vision data.

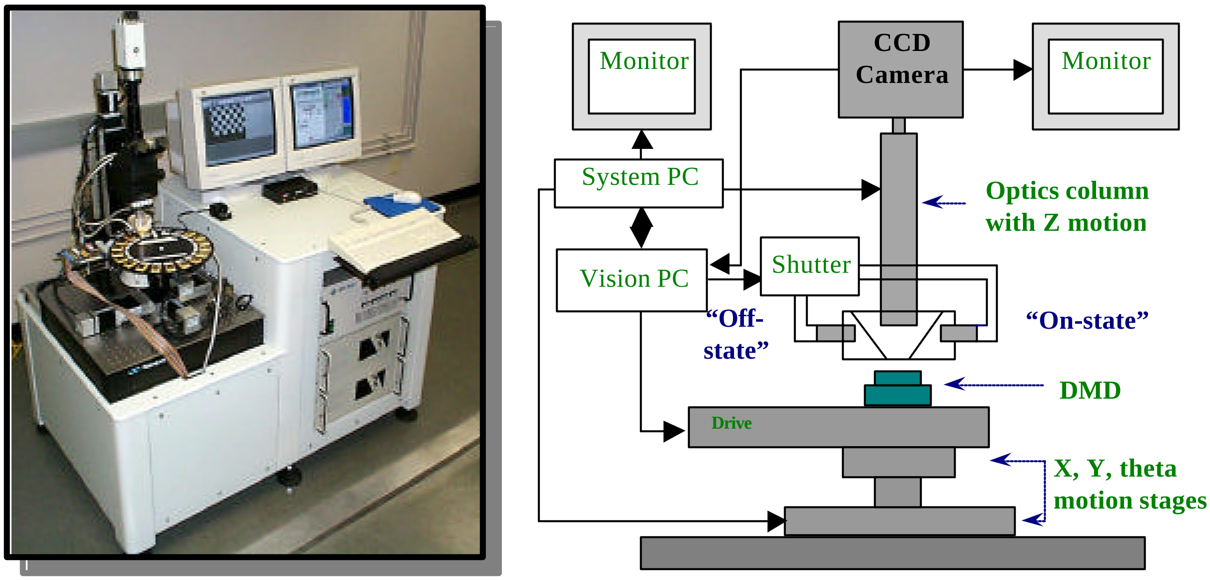

Figure 4 - DMD Test System

Each mirror is tested and inspected at fixed or variable operating conditions, as specified by the system software. In this way, the system can either test the DMD under fixed operating conditions (with or without an operating margin) or sweep a variety of operating parameters to determine optimum performance. This capability was key to developing an understanding of the DMD and led to numerous process and design improvements.

Two examples of parameters developed as a result of using the DMD Test System are a Bias/Adhesion Mirror Mapping (BAMM) sweep and a Solution Space characterization technique[2]. A version of the BAMM sweep was one of the first parametric techniques developed. The concept consists of varying one parameter while holding all other parameters constant. The example shown in Figure 5 demonstrates how a group of mirrors behave as the bias voltage applied to the mirror is increased. When bias voltage, the voltage applied to the mirror causing it to land, is increased from 11 volts to 15 volts, no mirrors land. As soon as the bias voltage increases to 16 volts, some mirrors land. All mirrors land by the time bias voltage reaches 17 volts.

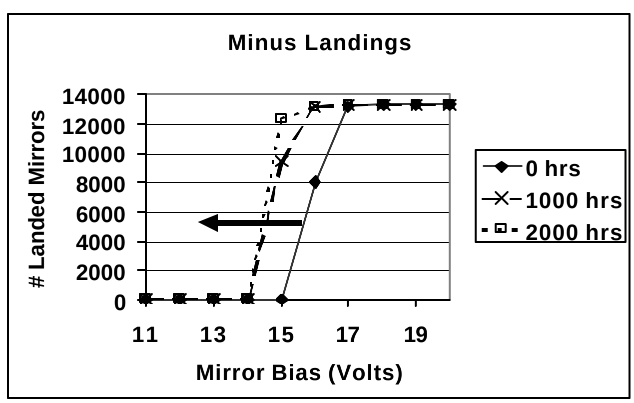

Figure 5 - BAMM Landing Curves

This parameter is referred to as the DMD landing voltage. It varies as a function of numerous process and design parameters. Consequently, it has been extremely useful as a monitor of device performance and is an essential parameter measured on every DMD lot. Note that the landing curve has a tight distribution. The voltage spread from when the first mirror lands to the last mirror is very small. This is a fundamental finding and is critical to DMD operation and mirror control. Measuring the landing curve also provides insight into operating margin. Operating margin is the difference between the voltage required to land a mirror and the optimum voltage needed to reliably control the mirror.

In addition, early DMD characterization testing found that landing curves changed as devices operated at high temperature and high duty cycle. As can be observed in Figure 5, these landing curves shifted to the left through a 2000-hour life test. By tracking the changes in the curves and the rate at which the curves move, the reliability modeling team predicted DMD lifetime. References (3) and (4) provide more details about this approach for predicting DMD lifetime.

Although slightly more complicated and time-consuming, the solution space characterization technique (Figure 6) provides significantly more information and is therefore more useful for early characterization testing. It varies multiple parameters and presents the results in a format that provides visualization of the interrelationships between control parameters. It is similar to a "schmoo" plot, often used for CMOS characterization. In this example, bias voltage and a timing parameter are varied. Figure 6 overlays two plots to show how the operating space changes through a life test. At each combination of operating conditions, the DMD test system calculates how many mirrors do not behave properly. The system places a value of "0.1" for each combination where all mirrors operate properly and outlines the total area with a dark line. This is the solution space at the beginning of the test. In other words, this is the area of the plot where all mirrors operate properly under all combinations of operating conditions. The larger the solution space, the more operating margin provided by the DMD. After a life test, the test system measures the operating parameters of each mirror again, plots the results and highlights the solution space in a different color. One can observe from the example that the solution space shrinks as the DMD operates under stressful conditions. This understanding led to improved mirror drive waveforms, more robust DMD designs, and tighter process controls. Consequently, characterization testing estimated that the DMD could operate under extreme conditions for many thousands of hours.

DMD Solution Space

Tbo	0.302	0.474	0.647	0.819	0.991	1.164	1.336
19	13238.1	13236.1	13236.1	13234.1	13224.1	13249.1	13230.1
19.5	4959.1	5741.1	6313.1	7142.1	6809.1	7409.1	7481.1
20	75.1	97.1	161.1	342.1	649.1	717.1	963.1
20.5	0.1	3.1	4.1	8.1	122.1	121.1	187.1
21	0.1	0.1	0.1	0.1	1.1	8.1	20.1
21.5	0.1	0.1	0.1	0.1	0.1	1.1	0.1
22	0.1	0.1	0.1	0.1	0.1	0.1	0.1
22.5	0.1	0.1	0.1	0.1	0.1	0.1	0.1
23	0.1	0.1	0.1	0.1	0.1	0.1	0.1
23.5	0.1	0.1	0.1	0.1	0.1	0.1	0.1
24	0.1	0.1	0.1	0.1	0.1	0.1	0.1
24.5	0.1	0.1	0.1	0.1	0.1	0.1	0.1
25	0.1	0.1	0.1	0.1	0.1	0.1	0.1
25.5	0.1	0.1	0.1	0.1	0.1	0.1	0.1
26	0.1	0.1	0.1	0.1	0.1	0.1	0.1
26.5	0.1	0.1	0.1	0.1	0.1	0.1	0.1
27	0.1	0.1	0.1	0.1	0.1	0.1	0.1
27.5	0.1	0.1	0.1	0.1	0.1	0.1	0.1
28	0.1	0.1	0.1	0.1	0.1	0.1	0.1
28.5	0.1	0.1	0.1	0.1	0.1	0.1	0.1
29	0.1	0.1	0.1	0.1	0.1	0.1	0.1
29.5	0.1	0.1	0.1	0.1	0.1	0.1	0.1
30	0.1	0.1	0.1	0.1	0.1	0.1	0.1
30.5	0.1	0.1	0.1	0.1	0.1	0.1	0.1
31	0.1	0.1	0.1	0.1	0.1	0.1	0.1
31.5	0.1	0.1	0.1	0.1	0.1	0.1	0.1
32	0.1	0.1	0.1	0.1	0.1	0.1	0.1

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Figure 6 - DMD solution space characterization technique

In addition to these two examples of characterization tests based on the DMD test system described above, DMD engineers have developed numerous other test techniques over the years. Some interesting techniques include laser based optical systems, optical photo-multiplier based systems, and laser Doppler vibrometers, among others. Each characterization test serves a specific purpose in order to increase our knowledge of how a DMD works and its performance limitations. This base of knowledge was then used to optimize designs, processes and mirror drive waveforms [5].

Characterization is performed on all new DMD designs, critical processes, and even packaging changes. For each proposed change, the product engineer coordinates an FMEA study and initiates applicable characterization tests. In the example of packaging changes, test plans place less emphasis on mirror dynamics and more emphasis on package integrity and environmental exposure. Changes to the mirror design require more emphasis on dynamic characterization and less on package integrity testing. Because of our long history of characterization testing, DMD engineers develop customized test plans for the design under evaluation. This saves time and resources.

5. RELIABILITY VERIFICATION

> You can't test reliability into a product; it must be designed in.

As each new DMD or DMD design change completes the characterization phase, it enters a comprehensive series of reliability verification tests. The tests are selected based on FMEA studies as well as the results of characterization testing. At this point, the tests can only demonstrate how reliable the design is and therefore measure the effectiveness of our modeling and characterization. When verification testing identifies failures, rapid corrective action is necessary in order to maintain time-to-market commitments.

Previous publications discuss DMD reliability testing in detail[3]. The purpose of each test was to identify and accelerate failure mechanisms as rapidly as possible. The earlier the tests are run, the better the opportunity to identify and eliminate failure mechanisms. The following sections summarize and update the results of some of the reliability tests developed for the DMD.

5.1 Hinge fatigue

Devices are routinely subjected to high temperature mirror cycle testing. The micromirrors are rapidly cycled from one side to the other at a rate much faster than in normal operation. The purpose is to determine if the hinges will wear out and break over extended operation. Throughout DMD development, devices consistently passed trillions (10^{12}) of mirror cycles with no hinge failures. One set of devices started test in December 1995 and is still on test. Nine DMDs have completed over 56,500 operating hours and over $3x10^{12}$ mirror cycles with no hinge fatigue failures to date. Under normal operation in a projector application, the mirrors accumulate this many cycles in 120,000 to 200,000 operating hours. Therefore, hinge fatigue lifetime is greater than 120,000 hours. For a business projector application where the projector may be used no more than 1000 hours per year, this equates to over 120 years without a hinge failure. Even for a consumer television where usage may approach 5000 hours per year, this represents a hinge lifetime of over 24 years.

Note that each of the nine DMDs discussed above consists of approximately 500,000 mirrors so the total number of mirror cycles is $13.5x10^{18}$ with no hinge fatigue failures. Based on the hundreds of DMDs that have completed this test with no failures, we conclude that hinge fatigue is not a concern.

5.2 Hinge Memory

Hinge memory is the only known life limiting failure mechanism exhibited by the DMD. The phenomenon occurs when the DMD is operated at high temperatures and high duty cycles. Although the mechanism behaves like metal creep, recent experiments indicate there is a significant contribution from surface effects. This mechanism is very predictable. It is also very controllable through design rules and process controls. DMD engineers are identifying many promising processes and designs that could eliminate the phenomenon.

The development of BAMM landing curves (figure 5) and the associated parametrics were key to hinge memory lifetime predictions. The landing curves behave in a predictable manner and shift in relation to hinge memory accumulation. This enables parametric plotting versus time, temperature, duty cycle and other variables. These parametric curves provide useful modeling inputs which means tests do not always need to continue to device failure. The reliability modeling team can develop models faster and with fewer resources.

Modeling activities associated with hinge memory have found that the dominant acceleration factor is a combination of temperature and duty cycle (how much time the mirror is directed to land on one side versus the other.) High temperature and high duty cycle provide accelerated test conditions. High temperature combined with low duty cycle results in significantly less hinge memory accumulation. For example, a 50/50 duty cycle (mirrors are directed to land on one side 50% of the time and the other side 50% of the time) develops no hinge memory at all, regardless of operating temperature. Likewise, operation at a high duty cycle combined with low temperature develops hinge memory at an extremely slow rate. Published results[4] have estimated hinge memory lifetime of greater than 11,000 hours at absolute worst case operating conditions and greater than 100,000 hours at normal operating temperatures (Figure 7). Follow-on studies are estimating the lifetime could actually be above 20,000 hours at worst case conditions and well above 200,000 hours under nominal temperatures and nominal duty cycles. This is more than sufficient for applications ranging from business projectors that typically operate in the extended operating range to consumer televisions that typically operate in a cooler environment. In addition, hinge memory is not a permanent degradation mode. Reversal of the mirror duty cycle will completely reverse previously accumulated hinge memory. Simple duty cycle patterns can therefore effectively extend hinge memory lifetime indefinitely.

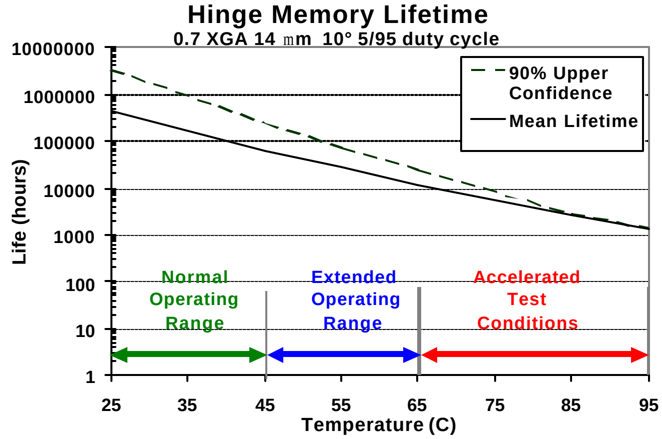


Figure 7 - DMD hinge memory lifetime estimates

5.3 Stiction

Similar to hinge memory studies, the development of BAMM curves was critical. Instead of landing curves shown in Figure 5, the DMD test system plots the voltage where mirrors release from the landing surface. When mirrors release with high bias voltage applied to the mirrors, then the surface forces holding the mirror down are obviously very small. Alternately, when mirrors stay landed, even when the test system removes bias voltage from the mirror, surface forces are presumed to be greater. Thus, BAMM release curves are an indirect measure of mirror-to-surface adhesion or stiction.

These curves and associated parametrics drive decisions concerning new designs and new processes. TI has developed detailed models of micromirrors. The models incorporate electrostatics and dynamics to predict mirror performance. With BAMM release curves, the models also relate the measured release voltages to estimated nanoNewtons of stiction force. Release curves also provide valuable process control information during DMD fabrication as well as critical reliability monitors for qualification and lifetime modeling. Stiction performance is not as predictable as hinge memory. Release curve metrics often indicate a bimodal distribution instead of a normal distribution. The addition of spring tips to the DMD micromirrors virtually eliminated concerns about short-term stiction failures. Process improvements and process controls have further improved DMD stiction performance to the point where lifetime estimates due to stiction are measured in tens of thousands of hours and predicted to exceed 100,000 operating hours.

5.4 Environmental Robustness

The DMD has always proven to be environmentally robust. DMD environmental qualification tests are based on standard semiconductor test requirements. Figure 8 provides a list of typical environmental tests (non-operating) used for design verification, qualification, and production sampling. Although a MEMS structure may appear fragile due to its microscopic dimensions, the DMD has demonstrated that the small scale is what actually enables robustness. The DMD mirror structure is effectively impervious to mechanical shock and vibration at low frequencies since the lowest resonance frequency of the mirrors is in the hundreds of kilohertz. Texas Instruments has tested thousands of DMDs through 1500g mechanical shock tests and 20g vibration tests with no failures due to mirrors breaking, with the exception of an occasional loose particle in the package cavity causing mirror damage.

Storage Life Cold/Hot	**-55/100C, no power**	**1000 hours**
Temperature Cycle	**-55/125C, air-to-air, fine/gross leak**	**1000 cycles**
Thermal Shock	**-55/125C, liquid-to-liquid**	**200 cycles**
		1000 cycles, info
Unbiased Humidity	**85C, 85% RH, no power applied**	**1000 hours**
ESD	**HBM only, 1 pos/1 neg, 2000V**	
	4000V information	
Latch-up	**25C, +/- 300mA**	
UV Light Sensitivity	**25C, UV Exposure**	**1000 hours**
Sequence 1	**1500g Mechanical Shock, Y only**	
	Vibration, 20g, 20-2000Hz	
	Constant Acceleration, 10Kg, Y1 only	
Sequence 2	**Thermal Shock, -55/125C**	**15 cycles**
	Temperature Cycles, -55/+125C	**100 cycles**
	Moisture Resistance	**10 days**

Figure 8 - DMD environmental tests

Thermal testing is very effective for package integrity testing. Robust packaging was critical to our early reliability development activity and remains critical today. In order to maintain the high-reliability reputation of the DMD, the package cavity must remain free of contamination and protected from the outside environment. This includes not only the mirror structure but also the window surface. The optical properties of the window are an important part of the superior image quality provided by the DMD. A series of rigorous environmental tests on each package design change assures it will remain reliable for the life of the product.

In summary, the results of all the reliability verification testing demonstrate that the design of the DMD is very robust and reliable.

6. RELIABILITY PERFORMANCE DURING PRODUCTION

> Every failure is an opportunity to learn.

As our development and qualification testing progressed, we found that the DMD had competitively superior reliability in addition to the superior image quality provided by DLP™ technology. All the early design, development, characterization, and testing effort resulted in a light modulating device that outlasts most product life cycles. Reliability modeling estimates of greater than 100,000 hours of lifetime are proving to be true.

6.1 Field Reliability

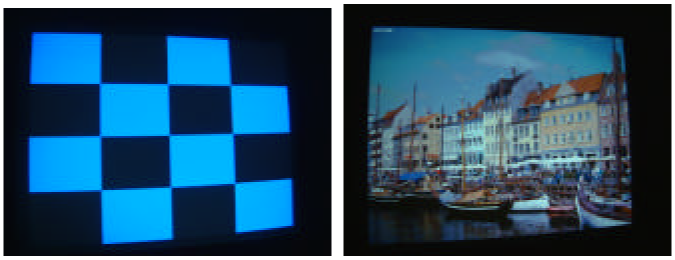
A recent review of production DMD field failures shipped between 1998 and 2000 resulted in an estimated failure rate of 1500 FIT (failures in time or failures per 10^9 operating hours.) A FIT rate of 1500 is equivalent to an MTBF of 650,000 hours. This is a respectable result considering the maturity of the technology and in comparison to competitive technologies. It even compares well with some of the more complicated integrated circuits, such as microprocessors.

Still, any failure is unacceptable. Failure analysis is an invaluable tool to identify root causes. In many cases, failure analysts needed to develop unique techniques to isolate failure mechanisms [6]. The DMD product engineer then analyzes the root causes and implements corrective actions. This feedback loop has been tremendously valuable as a learning tool to further improve DMD reliability. A study investigating the root cause of failures identified particles as the primary cause. Process improvements show a steady decline in failures due to particles. This improvement is showing up in reduced field failure rates as well. First-generation DMD field failure rate studies from 1996 through 1998 resulted in an estimated 7100 FIT. As stated above, recent studies estimate second-generation DMDs from 1998 through 2000 at 1500 FIT. Data for third-generation DMDs from 1999 through 2001 is still being reviewed with early estimates showing failure rates less than 1000 FIT. The trend is obvious and TI expects the trend to continue as DMDs transition into each subsequent generation.

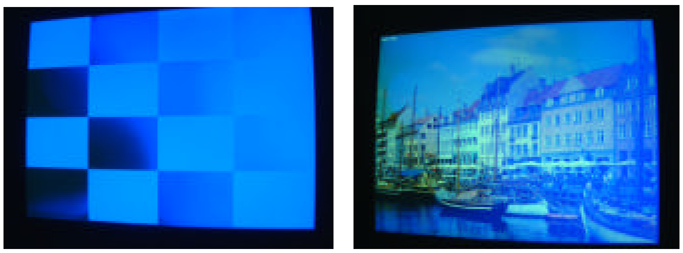
6.2 Picture reliability

Projector applications have demonstrated the advantages of the DMD as a reliable light modulator for years. The quality of the seamless image has also been widely touted. The ability of the DMD to maintain a high quality image over the life of the product defines picture reliability. Studies comparing DLP™ technology to Liquid Crystal Displays (LCD's) have demonstrated another significant advantage of the DMD. In one study, we evaluated the picture reliability of several high-definition televisions using DLP™ technology. Technicians recorded initial measurements and the televisions started life test. Throughout the life test, operators evaluated the picture. As of this writing, all systems have completed over 10,000 operating hours with no observable degradation to the picture.

In a second, more controlled study, TI purchased several portable business projectors using various light modulator technologies. Two DMD projectors operated alongside five LCD projectors and one Liquid Crystal on Silicon (LCOS) projector. The test technicians made detailed measurements throughout the test including lumens, contrast ratio, and colorimetry as well as an evaluation of the image quality. As expected, the DMD-based projectors are still operating after 4000 hours with only minimal change in parametric measurements and no observable degradation in image quality. In contrast, all LCD projectors have exhibited a severely degraded image in addition to parametric degradation. Figures 9a through 9d show images of the pictures for a DMD-based projector and an LCD-based projector after 3300 hours. All LCD projectors showed a visible degradation in image quality by 2500 hours with some degrading within 1400 hours. Figure 10 presents time-to-failure data using degraded image quality attributed to the light modulator as the metric. This study highlighted a significant advantage for DLP™ technology, especially for applications demanding picture reliability (image quality over time) as well as overall product reliability.



Figures 9a and 9b - Picture generated by a DMD after 3300 hours shows no degradation in image quality.



Figures 9c and 9d - LCD picture after 3300 hours shows significant degradation in image quality. First signs of degradation observed at 1200 hours.

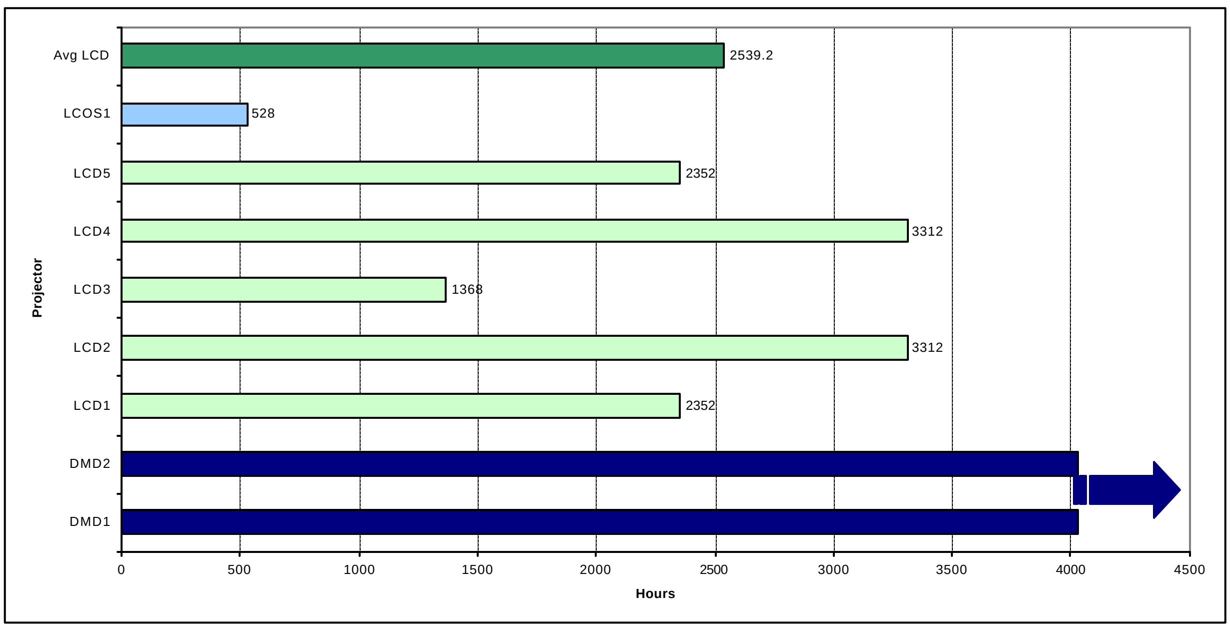


Figure 10 - Time to failure for different projector technologies.

7. MATURING OF MEMS

> Lessons experienced are not necessarily the same as lessons learned.

Unlike standard integrated circuits that take an electrical signal and convert it into another electrical signal, MEMS devices perform conversion functions that interact with the environment. Whether the function is acceleration, fluid pumping, mechanical motion or dispensing medicine, MEMS goes well beyond electrical signal processing. In the case of the DMD light modulator, we take an optical analog input and convert it into a digital format. Like most MEMS devices, the DMD was a new technology with many new issues to understand and resolve. In addition, TI addressed many system concerns unique to the DMD[7]. In fact, the DMD is more than a MEMS device since it is a micro-electrical-mechanical-optical-chemical system and therefore required a systems approach to development. A multidiscipline team spent several years developing an understanding of DMD interactions. This is virtually impossible in a laboratory environment, as production improvements require a production environment.

High volume production leads to rapid learning cycles. The coexistence of our development and manufacturing teams also contributed to rapid learning cycles. Without learning cycles, it is difficult to build on successes and avoid problems. TI has built a significant list of lessons learned. Some lessons resulted from well-structured experiments. Other lessons resulted from unforeseen issues during volume production. Either way, learning from these lessons provides a better product. Merely experiencing problems without implementing positive corrective actions frustrates both the producer and the customer.

In order for MEMS to mature as a technology, commercialization is critical. Numerous applications exist but the market has not embraced MEMS as the solution. The commercial market demands differentiation, especially for new technology. The potential for success is tremendous but the consumer needs to understand and appreciate the advantages of any new technology. As an example, companies pursue micromachined accelerometers not because they are micromachined, but because they provide the desired function at a competitive cost[8]. In the case of the DMD, the differentiation is design flexibility, superior image quality and long lifetime. The DMD is commercially successful not because it is a MEMS device but because it provides differentiation at a competitive price[9].

Although this is not a paper addressing marketing, the need for up-front marketing and a strong pull from the market cannot be overemphasized. The success of MEMS will rely more on market pull than it will on technical capability. The DMD has a strong demand due to the success of DLP™ technology-based products. This led directly to rapid learning cycles and is in turn leading to technological maturity and commercial success.

8. CONCLUSION

Testing and characterization provide valuable insight into how a device works and how it fails. Learning can occur during this stage of development since every failure is an opportunity to learn. However, the implications of ramping to high volume production are difficult to foresee. One can minimize interactions between design and process variability but rarely can a designer eliminate production problems. The DMD achieved its excellent reliability reputation through a methodical product development process: set goals, design to the goals, test, and redesign as necessary. DLP™ technology entered the market after the DMD achieved its minimum goals. Market acceptance due to differentiation led to increased demand that in turn led to high volume production. High volume production allowed additional rapid learning cycles and further improvements in performance and reliability.

Today, lifetime estimates for the DMD exceed 100,000 operating hours. The DMD is robust mechanically, electrically and environmentally. When assembled into a DLP™ technology-based projector, the DMD also exhibits like-new image quality for many thousands of hours. The DMD could not have achieved these reliability results without early, aggressive testing and thorough, creative characterization activities.

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