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**Thomas J. Suleski
Winston V. Schoenfeld
Jian Jim Wang**
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MEMS Reliability - Coming of Age

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ABSTRACT

In today's high-volume semiconductor world, one could easily take reliability for granted. As the MOEMS/MEMS industry continues to establish itself as a viable alternative to conventional manufacturing in the macro world, reliability can be of high concern. Currently, there are several emerging market opportunities in which MOEMS/MEMS is gaining a foothold. Markets such as mobile media, consumer electronics, biomedical devices, and homeland security are all showing great interest in microfabricated products. At the same time, these markets are among the most demanding when it comes to reliability assurance. To be successful, each company developing a MOEMS/MEMS device must consider reliability on an equal footing with cost, performance and manufacturability.

What can this maturing industry learn from the successful development of DLP[®] technology, air bag accelerometers and inkjet printheads? This paper discusses some basic reliability principles which any MOEMS/MEMS device development must use. Examples from the commercially successful and highly reliable Digital Micromirror Device complement the discussion.

Keywords: MEMS, MOEMS, Reliability, FMEA, Accelerated Testing, Stress Testing

1. RELIABILITY: A BUILDING BLOCK

Consumers often focus on price while assuming the product is reliable. After all, why would a company sell a product that is not reliable? Because of the consumer's focus on price, some businesses may overlook the importance of including reliability as a fundamental building block along with cost and performance. The absence of reliability can lead to disastrous consequences. Lives are lost in the worst case. Businesses fail, profits fall and reputations are tainted in less critical situations. Is a 99% success rate good enough in our daily lives? In some cases this may be acceptable whereas in other cases, probably not. Airlines proudly report a success rate of greater than 99% in getting luggage to its destination. Based on a recent report, one in every 138 checked bags was lost or misdirected in 2007. This may seem like a robust process, 99.3% success rate, but it results in close to five million passengers impacted by misrouted luggage [1]. Would this be good enough for flight controllers? DFW Airport handles nearly 700,000 flight operations per year [2]. A 99.3% success rate resulting in 5,000 misdirected aircraft per year would be a serious safety risk and completely unacceptable. Based on cost versus risk, airports have developed a much more robust and reliable system for handling aircraft operations than has been developed for baggage handling. Consumers demand it.

What is an acceptable success rate for a system, device or process? This depends on numerous factors the most important of which is the customers' expectations. Understanding and meeting customer expectations is paramount to building a good relationship. MEMS devices are often uniquely suited to meeting a customer's reliability needs but the challenge is proving it. The Digital Micromirror Device (DMD), a digital optical MEMS technology at the heart of DLP[®] televisions, cinemas, and projectors [3], demonstrates MEMS reliability on a daily basis. DMDs in these applications rarely have even 1 pixel defect through thousands of hours of operation thus demonstrating mirror reliability greater than 99.9999%.

After many years of predicting growth in the MOEMS/MEMS, industry, growth is finally occurring. There are many examples of growing successful MEMS businesses besides the well-known DMD in DLP projection applications and accelerometers in automobile air bags. Figure 1 shows the top 30 MEMS manufacturers in 2006. Consumer markets are growing rapidly although most consumers are probably not even aware of them. Inkjet printheads have been using MEMS for years. MEMS gyroscopes have been widely integrated into camcorders since 1998 to provide optical stabilization. Hard disk drives have used MEMS accelerometers as a protection feature since 2003. In 2006, Nintendo

introduced the Wii interactive computer game to the public incorporating inertial MEMS sensors [4]. None of this would be possible without cost, performance and reliability advances.

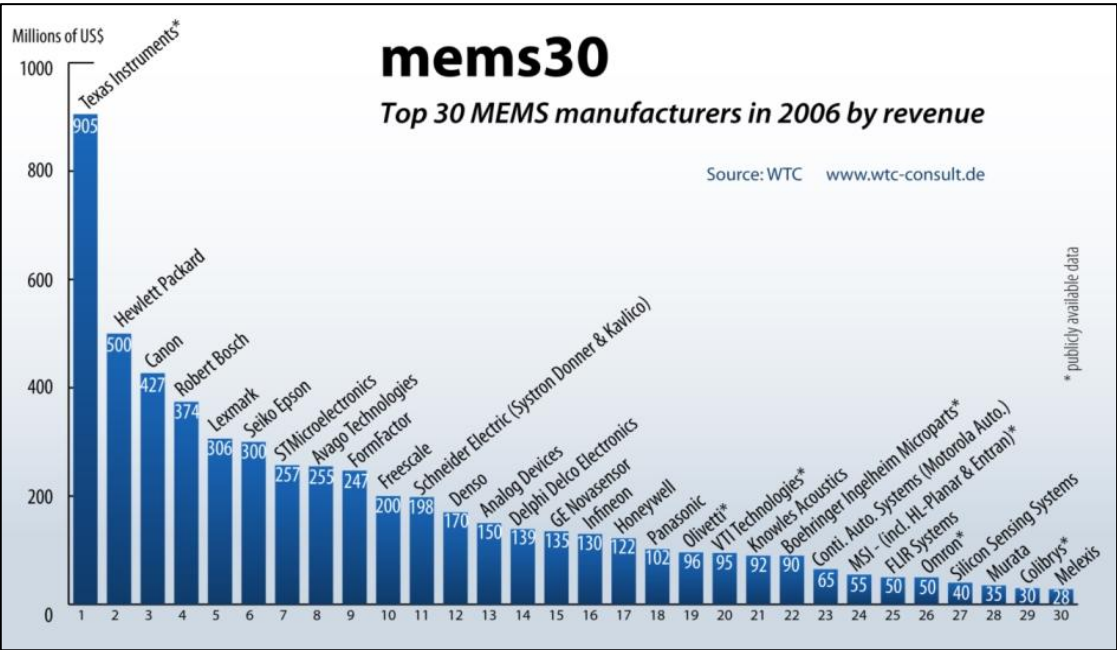


Figure 1 – Top 30 MEMS manufacturers in 2006 by revenue. The top products include optical MEMS (TI), inkjet printheads (HP, Canon, Lexmark, Seiko Epson, STMicroelectronics, and Olivetti), and automotive products (Bosch).

2. THE SYSTEM RELIABILITY DEVELOPMENT PROCESS

Since MEMS devices are micro-systems, the concepts developed by systems reliability engineers apply directly to MEMS. Many of these concepts originated to support the high reliability demands of military electronics. Over the years, commercial products adopted and adapted the concepts to address the increased demand for reliability in the consumer space. Now, the MEMS industry is following the same path by focusing on the methods rather than any specific tests.

For example, the much maligned [5] and often overused bathtub curve shown in Figure 2 is an excellent way to take a complicated system, either macro or micro, and break it down into discrete segments. The focus should not be on the

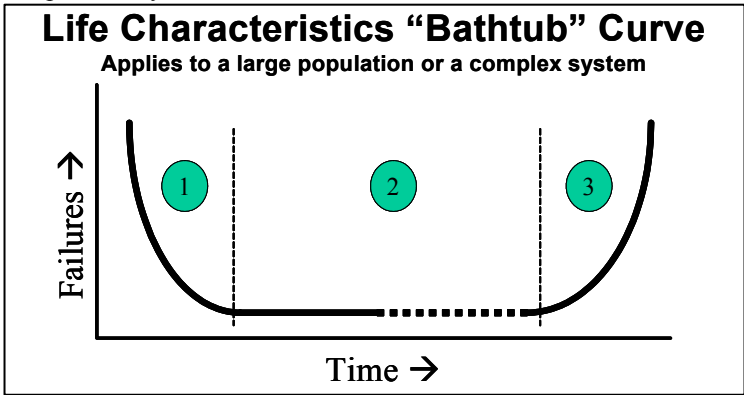


Figure 2 - The classic bathtub curve with 3 distinct segments: (1) early failures, (2) useful life, and (3) wear out or end-of-life.

statistical accuracy of the curve but on the segmentation of the problem. Regardless of the statistics, engineers must determine the root cause of failures and continuously improve reliability in product design and manufacturing techniques. As much as we would like to have no failures over a fixed period of time, as shown in Figure 3, it will rarely happen in practice. There will be yield fallout in production, there will be a number of escapes through the inspection and test process resulting in early customer failures, there will be some weaker devices fail during use due to overstress, and there will eventually be failures due to wear out.

A large population of complicated systems tends to follow the bathtub relationship. Each segment of a system's life cycle requires a different corrective action approach. For example, more effective burn-in testing or stress screening can identify early failures in segment 1 of Figure 2. Any defective units that make it through the production test will result in a customer failure. A customer's production test will often catch defects but some will still escape resulting in an end-user failure. An example of reducing defects with the DMD involved improved correlation of inspection criteria. Since the DMD displays an image, the criteria for acceptance include visual inspection of the displayed image in the customers' product. Test equipment correlation as well as inspection operator training resulted in an order of magnitude improvement in Texas Instruments' outgoing quality as measured by the customers' production yield. Segment 2 of the bathtub curve is usually difficult to understand and improve. The most effective approach is to design the product for the worst-case intended application. A more robust design survives, not only the intended use, but abusive use as well. The challenge is to not over-design and add unnecessary costs to the product. Conservative

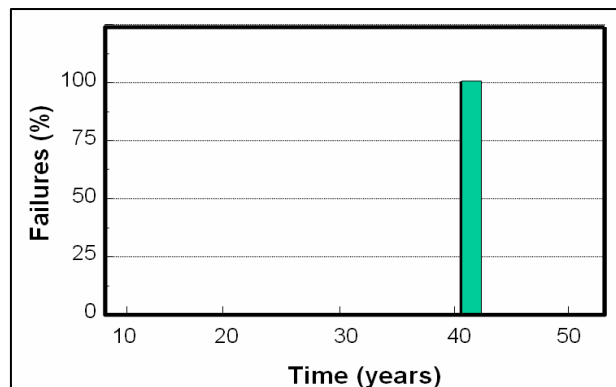


Figure 3 - The ideal bathtub curve. No failures for 40 years then everything fails the next day.

engineers like to design to the worst, worst, worst-case condition. This will almost assuredly result in a product with a cost structure that will not support the intended application. Designing for a typical consumer, not the few consumers that might use the product in extreme cold or extreme heat, is often the most effective approach. Exceptions may include medical applications or space applications where failure is not acceptable under any circumstances.

To address lifetime issues in segment 3, designers can select different materials that last longer before wearing out. Other options include defining drive circuits that extend lifetime, and adding redundant systems. Are all of these actions required? It depends on the cost versus risk analysis and what the customers' requirements are. It is imperative that the reliability of any system take into account the risks in each segment of the bathtub curve and address them appropriately. Otherwise, the results will be customer dissatisfaction, excessive warranty costs and/or a bad reputation.

3. IDENTIFYING AREAS OF RISK

A Failure Modes and Effects Analysis (FMEA) is typically a requirement for developing military equipment due to the complex nature of the systems. FMEA involves brainstorming potential failure modes, identifying associated root causes, assigning levels of risk (severity, detectability, and occurrence), and following through with corrective actions. Component development does not often use the approach. Since MEMS devices are literally systems, albeit on a micro-scale, the FMEA approach has proved to be an effective method of identifying potential failure modes and mechanisms [6]. Early development of the DMD utilized FMEA as a way to partition the complex system into specific areas of risk. This allowed TI to prioritize and focus on the areas of greatest concern [7, 8].

Each MEMS technology may have some unique failure modes and mechanisms that set it apart from other MEMS or solid-state electronic technologies. Therefore, the FMEA methodology should be customized to account for these unique differences, prioritizing them according to their overall significance within the realm of more traditional failure modes and mechanisms. Depending on the MEMS technology, examples may include packaging concerns, stiction, particle sensitivity, wear, chemical interactions, or mechanical shock integrity. The more thorough the FMEA, the better one can establish a reliability plan to ensure device robustness.

NASA guidelines for MEMS development use the same approach as described above. For example, JPL Publication 99-1, "MEMS Reliability Assurance Guidelines for Space Applications" [9] specifically states, "The focus of this guide is upon methods rather than tests..." and "...the vast difference in types of MEMS devices means that each set of devices may require unique acceleration conditions." Increasing temperature in solid-state electronic systems will accelerate failure mechanisms. "In MEMS...it may be temperature, humidity, vibration, or a number of other factors that limit device lifetime and accelerating one failure mode may decelerate another [9]." That last statement, in particular, succinctly summarizes the challenges associated with MEMS reliability. A more recent publication states that, "...the

failure modes of MEMS can be very different from those of solid-state electronics. Therefore testing techniques must be developed to accelerate MEMS-specific failures [10].” The importance of using a structured approach like FMEA cannot be overstated. Regarding the DMD, TI developed many unique tests as a result of the FMEA process.

Not only are there unique failure mechanisms associated with MEMS architectures, but also MEMS materials and manufacturing methods have unique characteristics. Tronics Microsystems documented an example where the production yield of an inertial device increased from 43% to 67% within 2 years through the systematic analysis of 17 identified failure modes [11]. FMEA can be applied to a foundry process to highlight manufacturing weaknesses throughout the entire production loop. Statistical Process Control (SPC) is an excellent way to address concerns highlighted by the FMEA [11].

An interesting aspect of MEMS devices is that they all interact with the environment in some manner. The DMD converts an analog light source into digital pixels for high quality displays. Automobiles use accelerometers, tire pressure sensors, and stability control to interpret and respond to the environment. The medical industry uses nanopumps to deliver drugs to patients. The reliability engineer must consider all these unique applications very carefully. The best approach is to assemble a group of experts from diverse disciplines, the more diverse, the better the FMEA. Brainstorm all possible failure modes and failure mechanisms. How can the device fail? When will it fail? When it fails, what happens? What is the impact to the system and to the user? Some people find this process invigorating while others find it frustrating to focus exclusively on the negative aspects of the design. Certainly, a properly managed FMEA is an educational experience where everyone in the room learns about the inner workings of the device.

The most important aspect of an FMEA is the follow-up and corrective action closure. If a team does an excellent job of brainstorming and stops there, the entire process was a waste of time. Discuss and rank each concern. Determine which ones need immediate attention. Establish an action plan to address each concern: analysis, design, inspection, or test. Then close the loop on the FMEA by updating the concerns with the actions taken.

4. FAILURE LEADS TO SUCCESS

To understand the robustness of a design and to thoroughly explore the items identified in the FMEA, you must find failure limits. A critical methodology used by systems reliability engineers that must also be applied to MEMS is the test-to-failure philosophy that includes the maxim to continually explore the design limits of the product. Some quotes from “Success through Failure” [12] follow:

“The Paradox of Design: Things that succeed teach us little beyond the fact that they have been successful; things that fail provide incontrovertible evidence that the limits of design have been exceeded. Emulating success risks failure; studying failure increases our chances of success.”

“When failure is left behind, success leads with a confidence that the uncharted future does not warrant.”

“A profession that never has accidents is unlikely to be serving its country efficiently.”

“Given the faults of human nature, coupled with the complexity of the design of everything...it behooves us to beware of the lure of success and to listen to the lessons of failure.”

New technologies, such as MEMS, are ripe for exploring design limits similar to those shown in Figure 4. Whether the stress is temperature, voltage, vibration, or shock, knowing where a device ceases to function (operating margin) and where permanent damage occurs (destruct margin) is invaluable. For example, if the device maximum operating specification is 65°C and stress testing demonstrates continued operation up to 85°C, then you know there is substantial margin. If the device fails at 70°C, then there is a chance of customer failure and also a distinct risk that process variation will result in some future lots failing even when operated within specification limits. In this case, the designers should implement a corrective action. Likewise, if the device can be exposed to 100°C without permanent damage, there is substantial margin but if the device is damaged when exposed to 70°C, then it is likely to fail in a customer’s application resulting in dissatisfaction. While exploring the design limits in response to an FMEA concern, engineers

often uncover unexpected failure mechanisms. This occurred frequently during DMD development. Finding failures early helped speed the development process and ended with a robust design delivered to customers. The DMD philosophy was, and still is, that “every failure is an opportunity to learn” and that “the only bad test is a test where you don’t learn anything [8].”

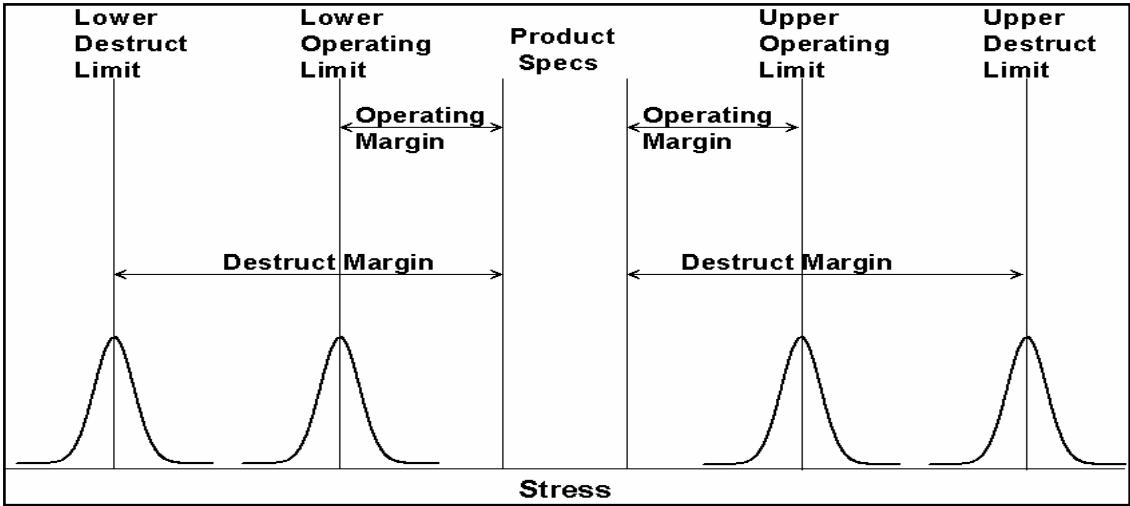


Figure 4 - Accelerated Stress Testing or Test-to-Failure Approach.

5. ACCELERATED STRESS TESTING

Accelerated testing is an excellent method to highlight weaknesses and determine how much margin the device has to its intended use conditions. The approach is to test-to-failure, find the weaknesses, evaluate the root cause, determine if the corrective action is practical, analyze the risk/benefit ratio of implementing the corrective action, and updating the FMEA as shown in Figure 5.

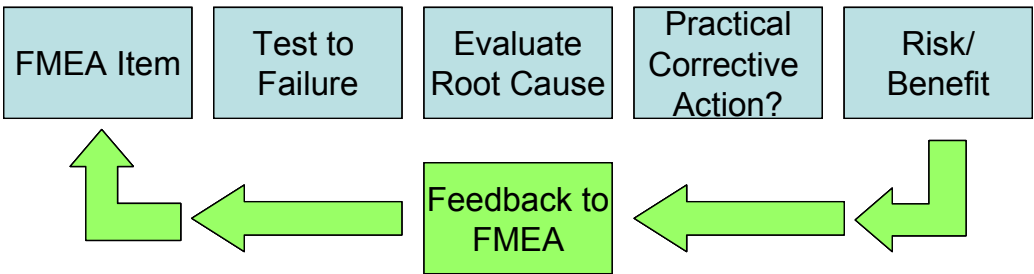


Figure 5 – Test-to-Failure approach with closed-loop feedback to the FMEA.

A survey performed by the MEMS Industry Group (MIG) in 2004 found that “70% of MEMS designers and suppliers perform accelerated life testing [13].” The survey also found that, “Over 80% of those surveyed indicated...that average lifetime for a MEMS device is 15 years.” One question comes to mind; if the MEMS industry measures lifetime in years and 30% of the MEMS industry is not using accelerated life testing techniques, how are they demonstrating their reliability? Computer simulation is a possibility but its accuracy is limited without test data to support it and refine it. What is the best way to demonstrate the reliability of your product, first to yourself and then to a potential customer? For lifetimes measured in years, the only practical method is accelerated life testing or accelerated stress testing.

Throughout the early development of the DMD, accelerated life testing was used extensively as it still is today. One example addressed an early FMEA concern about the hinge. Several DMDs started an accelerated life test in December

1995. They were tested most recently in December 2007. After 12 years and over 100,000 actual operating hours, there have been no hinge fatigue failures. This is an accelerated test where the mirrors are cycled much faster than in normal operation. Each DMD mirror has cycled from on-to-off 5.30×10^{12} times throughout the test which is equivalent to over 360,000 operating hours without a fatigue failure. The 9 DMDs on test each have 500,000 mirrors; each mirror has cycled 5.30×10^{12} times for a total of 23.9×10^{18} mechanical movements.

These are impressive numbers but what do they mean? One conclusion is that micromechanics behave differently than macromechanics. This was critical to developing the DMD. Early models predicted the mirrors would fail due to fatigue cracks after several billion cycles. The test-to-failure approach quickly demonstrated that MEMS behave in a fundamentally different way. This led to a better understanding of thin film properties and the theory that stresses are relieved on the surface of amorphous micro-structures instead of at grain boundaries in macro-structures. Without using the test-to-failure approach, this important finding would have been missed.

Other accelerated stress tests have had equally interesting findings. Vibration and shock testing of the DMD confirmed that micromirrors are effectively immune to mechanical motions in the kilohertz range or less since the mirrors' resonant response is in the range of 100 KHz to 2 MHz or higher depending on the resonant mode and whether the mirror is in the unenergized (flat) state or is at the actuated angle of ± 12 degrees. As a result, DMDs are robust during normal handling and assembly processes. In addition, DMD environmental qualification tests (Table 1) are able to use stresses well beyond typical applications as a method of finding design or process weaknesses. Through the use of thermal shock and temperature cycling, TI found window seal problems with early DMD packages and eliminated them prior to production. Maintaining the environment inside a MEMS package can be a concern for some devices. Sandia National Labs found that too much humidity can cause failures, as expected, but surprisingly, too little moisture can also cause defects [14].

Qualification Test	Test Description	Hours/Cycles (minimum)
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
Sequence 1	1500g Mechanical Shock, Y only Vibration, 20g, 20-2000Hz Constant Acceleration, 10Kg, Y1 only	
Sequence 2	Thermal Shock, -55/125C Temperature Cycles, -55/+125C Moisture Resistance	15 cycles 100 cycles 10 days

Table 1 - Typical DMD environmental tests

The most impressive accelerated stress test ever performed on a complete DLP system was the one performed by Raytheon Systems Company in 1997. They used a Highly Accelerated Life Testing (HALT) approach to validate that their rugged display could survive stringent military environments. Tests on the entire display system included cold operation down to -71°C , hot operation up to $+97^{\circ}\text{C}$, thermal shock cycles from -80°C to $+100^{\circ}\text{C}$ at a rate up to 60°C per minute, and 3-axis random vibration up to 45Grms. The tests uncovered some minor design flaws but the display performed well in excess of the customer's expectations. The components comprising the DLP technology portion of the display (DMD, color wheel, and ASICs) performed flawlessly throughout the test [15]. TI does not recommend using DLP projectors in such a severe environment but it is good to know that they can survive, thanks in part to the MEMS device at the heart of the system.

TI has drawn an interesting conclusion from MEMS test results over the years as have other MEMS manufacturers - MEMS devices are robust because they are small. At first this seems to go against common sense but not if one considers the appropriate scaling laws. For example the strength to weight ratio scales as area over weight ($l^2/l^3 = l^{-1}$). This is the reason an ant can carry many times its own weight, whereas a human cannot.

Discera developed a MEMS oscillator for a high-reliability military application. The oscillator has already survived shock testing up to 14,000g with simulations predicting survival up to 100,000g. Discera contends the superior shock resistance is due to “the MEMS oscillator’s gravity-defying weight [16].” ADI states that MEMS gyroscopes are smaller, use much less power, and are more tolerant to vibration than their macro-counterparts. “Their immunity to vibration and shock comes from their being so small that their resonant frequency is very high...compared to normal gyros [17].” So it appears that MOEMS/MEMS devices may actually have a fundamental reliability advantage over their macro counterparts.

6. COMPETITIVE ASSESSMENT

It is critically important to understand the competitive landscape including competitive reliability. There are several questions that need to be considered as a company enters new markets or tries to grow existing market share:

1. Do you have a competitive advantage or disadvantage?
2. Is your product over-designed or under-designed for its application?
3. Are you meeting or exceeding your customers’ expectations?
4. Are there related markets where reliability is valued more or less?

By gaining a better understanding of the competition and the market in general, a business can determine future strategies. In some cases, one can gain market share through improved advertising and marketing, in other cases, one might determine that the product is over-designed for its intended application and therefore too costly.

In the case of the DMD and DLP technology, an assessment of competitive technologies highlighted a significant advantage in applications requiring long life under high stress conditions (e.g., high temperature, bright light, and continuous operation.) Compared to analog technologies, a digital optical MEMS technology has exceptional stability of image quality over time. Because the MEMS structure is operating in a digital mode, it is not sensitive to the analog changes in its structure that may develop, until those changes reach a level that cause a switching failure or “hard” defect.

The bottom line then is to design and manufacture the DMD so that at the end of its expected lifetime under the harshest of operating conditions, there is still (digital) operating margin to spare. So instead of failing “gracefully” like analog technologies, it doesn’t fail at all [3]. This life characteristic is an example of the ideal bathtub curve in Figure 3.

Other MEMS devices have distinct advantages in reliability, size, weight, power consumption and other performance parameters. For example, Hewlett Packard touts the reliability of their MEMS-based inkjet printhead in a brochure where they say they have brought together “proven silicon-based Micro Electro-Mechanical Systems (MEMS) technology and innovative piezoelectric inkjet technology... The new printhead is highly durable and reliable... [18].” Another interesting statement in this reference is, “MEMS technology was imported from semiconductor fabrication methods. It enables micron-scale mechanical and electrical components to be built on a silicon chip.” The use of existing semiconductor tool sets, processes and methodologies is another advantage of MEMS. Even packaging, historically a challenge for MOEMS/MEMS, is taking advantage of the cost-effectiveness and broad availability of CMOS processing technology to develop packaging techniques [19]. The infrastructure and knowledge is in place to rapidly reach the reliability levels already achieved by the mature semiconductor industry. The key for each MOEMS/MEMS device will be to identify its differentiating feature(s), achieve parity on other features (like cost), and prepare for entry into a competitive market.

7. CONCLUSION

MOEMS/MEMS devices are becoming more commonplace every day. Consumers will demand high reliability along with performance and pricing pressure. So far, the industry as a whole has responded appropriately. There are numerous examples of MOEMS/MEMS devices with excellent reliability resulting from well-designed products and well-structured reliability approaches. There is nothing that makes developing MOEMS/MEMS any more challenging than mature technologies other than there are more unknowns to discover. If the MOEMS/MEMS industry continues to use the reliability development methods that have been successfully applied to mature technologies, the journey will continue to be an exciting and rewarding adventure for all involved.

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