INFOTEH-JAHORINA Vol. 13, March 2014.

MEMS Micromirror Arrays: Some Reliability Issues

Ivanka Stanimirović, Zdravko Stanimirović
IRITEL a.d. Beograd
Belgrade, Republic of Serbia
inam@iritel.com; zdravkos@iritel.com

Abstract— **As the design of MEMS micromirror arrays matures and their application extends, the reliability issues become increasingly important. This paper summarizes the current state of knowledge when reliability of MEMS micromirror devices is in question. Four major failure modes that are common for all micromirror devices and that are likely to occur either during production or during operation will be discussed.**

Key words – Micro-electro-mechanical device; MEMS micromirror array; reliability; failure mechanisms;

I. INTRODUCTION

MEMS micromirror arrays (Figure 1) are among the most commercially successful micro-electro-mechanical (MEMS) devices [1] – [4]. Functions of the micromirrors are divided into three categories that correspond to the degrees of motion of micromirror operation:

- 1D configuration that allows the micromirror to control reflected light by tilting about a single axis, typically parallel to the plane of the micromirror array,
- 2D configuration that allows tilting of the micromirror along orthogonal positions parallel to the plane of the micromirror array, and
- 3D configuration that allows steering light along orthogonal positions parallel to and perpendicular to the plane of the micromirror array.

By rerouting optical signals directly, MEMS technology enables maintaining signal fidelity and continuity by creating an all-optical switching network. This technology may potentially replace existing electronics used for re-routing optical signals. Other applications of optical MEMS include digital light projection systems for displays. The most successful MEMS micrommiror array device is commercially available Digital Mirror Device (DMD) fabricated by Texas Instruments, USA. Televisions, home theater systems and business projectors using Digital Light Projection technology rely on a single DMD chip configuration providing high static and dynamic image quality. However, there is a general misconception that mechanical devices are not reliable. MEMS micromirror arrays are mechanical, as well as electronic devices, and for that reason they are supposed to wear out and brake down. New manufacturing processes, new materials and new testing methods allowed production of MEMS micromirror devices with remarkable performances. Such arrays exhibit particular metrology needs, and accuracy and reliability are the key factors for their successful commercialization. Performances from one device to the next can vary depending on the micro-fabrication process and the device geometry. For that reason, it is difficult to reliably ensure accuracy and repeatability of the actuator positions. MEMS micromirror array reliability analysis is extremely important to identify and understand the different failure mechanisms since they require interaction with the environment to perform their mission. A critical part of understanding the reliability of micromirror array comes from understanding the possible ways in which the system may fail and some of the key issues applicable to most MEMS micromirror arrays are discussed in this paper.

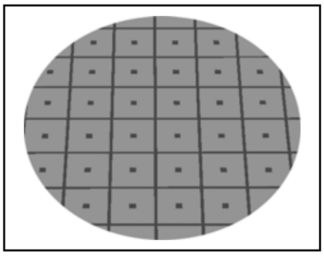

Figure 1. Schematic of MEMS micromirror array

II. MEMS MICROMIRROR ARRAY RELIABILITY

Reliability for MEMS micromirror arrays is identified as the next manufacturers challenge for the forthcoming years due to a growing market and stricter requirements. It is necessary to understand both technologies related variables as well as external variables such as environmental and operational conditions. MEMS reliability analysis is extremely important to identify and understand the different failure mechanisms that can be implicit. For that reason, a failure mechanism is defined as the physical cause (mechanical, chemical, or thermal) of the failure in the system. MEMS failure mechanisms are more complicated than those in microelectronics for several reasons:

- MEMS micromirror devices are designed to interact with environment at various environmental conditions (e.g., temperatures),

• they are usually hermetically sealed and they are expected to have long-term performances

• some of the failures is impossible to predict (e.g., stiction of the landing tip induced by the presence of moisture in the package),

• reliability testing for MEMS devices is not standardized unlike IC and microelectronics,

• for every new device new testing procedures need to be developed.

Design for test is important as well as performing parametric testing, testing during assembly, burn-in and final testing, testing during use, etc. Testing during assembly is of utmost importance for MEMS micromirror arrays. It has two purposes. The first is to determine which devices are ready for the packaging process and the other is monitoring the yield of the packaging process. After the assembly devices are subjected to "burn-in" tests because packaged micromirrors may fail to perform due to the invasion of unwanted foreign substances such as dust particles and moisture. The main purpose of this test is to induce "infant mortality" failure on the manufacturing premises but not during operational lifetime (Figure 2). Testing during use ensures proper functioning of the device for the intended application.

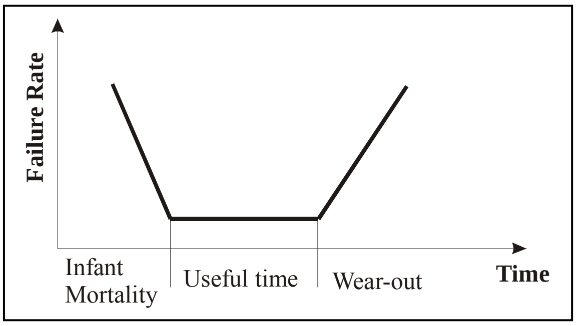

Figure 2. Device failure rate curve

When MEMS micromirror arrays are in question, several life limiting factors may come to mind such as: temperature, stress, voltage, chemical, light and mechanical factors [5]. However, four main potential threats to MEMS micromirror device reliability have been identified:

1. stiction,
2. fatigue,
3. hinge memory and
4. environmental robustness.

These threats are common for all MEMS micromirror arrays and in the following parts we discuss each of them in more detail.

A. Stiction

One of the potential failure mechanisms of MEMS mirror arrays is stiction. Stiction occurs when surface adhesion at the contacting interface exceeds the restoring force. In case of the MEMS mirror array, excessive adhesive force between the landing tip and its lending site may lead to stiction failure of the device. When the electronic reset sequence is applied, sufficiently high adhesive force may obstruct the movement of the mirror. Adhesion may be driven by either capillary condensation or van der Waals forces. Capillary condensation is affected by moisture and surface contamination, while van der Waals forces are affected by surface roughness [6]. Since device dimensions are minute, gravity and other body forces do not play a significant role. Capillary water condensation causes the landing tip of the mirror and adequate landing site to become stuck. A partial vacuum is produced at the interface due to the surface tension and great forces are required to pull the tip and the landing site apart. Van der Waals forces are short range forces which cause materials to be attracted at the molecular level. The vulnerability to stiction can be significantly reduced by surface passivation coatings, the use of critical point (CO_2) drying of MEMS devices and moisture free packaging [7]. However, the best way to avoid stiction failures is to eliminate presence of contacting surfaces by using adequate design or to enhance restoring force. Therefore, the usually used methods for stiction elimination are:

• implementation of springs on the landing tips of the mirror (Figure 3),

• enclosure in a controlled atmosphere,

• sealing in a robust hermetic package,

• thin self-limiting anti-stick layer deposition.

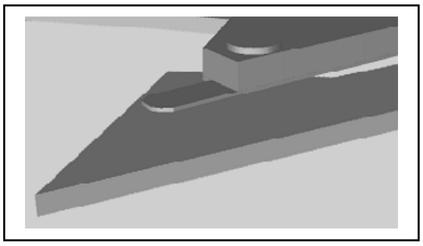

Figure 3. Schematic of the spring tip and its landing site

Implementation of spring tips was introduced for the first time during development of DMD (Digital Micromirror Devices, Texas Instruments, USA) when it was observed that adhesion forces were too great to deliver a reliable device. During reliability testing the measurement of the distribution of surface adhesion across the device was performed in order to determine the number of operating devices under different switching voltages. It was observed that, as the magnitude of the voltage was decreased, certain mirrors seized to function due to adhesion forces. In order to avoid stiction failures, springs on the landing tips of the mirror are usually being implemented. When the mirror landing tip lands on its landing site the spring bends and stores energy that will assist the mirror in taking off the surface when the reset pulse is being applied and bias voltage is being removed. Further actions that prevent mirrors from sticking are enclosure in a controlled atmosphere and robust hermetic packaging. In that way, the presence of moisture is being greatly reduced if not completely eliminated. Also, anti-stick layer are commonly being used to lower the surface interaction energy and prevent stiction. These layers provide hydrophobic surfaces on which water cannot condense and capillary stiction will not occur. However, the reliability and reproducibility of these layers is an important issue because of the high temperatures required in MEMS packaging process steps.

B. Fatigue

Fatigue is another mechanism that impacts the lifetime of MEMS device. Stress from repeated motions, even significantly below the crack strength, leads to crack growth and eventual failure. When micromirror arrays are in question, each micromirror is hinged so it can rotate. Having in mind that each mirror will be switched thousands of times per second, hinge fatigue should be taken into consideration. In order to avoid fatigue, micromirror hinges are usually realized using thin-film technology. The fatigue properties of thin-film layers are different from those of bulk materials. Metal thin films exhibit much less fatigue than do their macroscopic counterparts [8]. Thin-films have less stiffness (the property of a material that causes the material to resist bending) and therefore are less prone to breaking. Fatigue models are based on a movement of dislocations to the surface of the material forming fatigue crack after enough damage has been accumulated. Micromirror hinges are basically thin-films and they do not have internal crystal structure because they are just a few grains thick. For that reason, not enough damage will accumulate on the surface to form fatigue cracks. However, having in mind that the fatigue properties of thin films are often not known and that fatigue predictions are error prone, hinge structural materials should have material strength that far exceeds the maximum stress expected.

C. Hinge Memory

Unlike hinge fatigue, hinge memory poses a significant threat to MEMS micromirror device reliability. It is very significant life limiting failure mode that occurs when a micromirror operates in the same direction for a long period of time. When the bias voltage is removed the mirrors should return to a flat state. Their return to a non-flat state is known as a hinge memory effect (Figure 4). The angle between the flat and non-flat state is called residual torque angle. As this angle increases, at one point the mirror won't be able to land to the other side anymore and, due to hinge memory failure, failed pixel will be clearly visible. Main contributors to hinge memory failure are duty cycle and operating temperature, but the main cause of this type of failure is the creep. Creep is the slow movement of atoms under mechanical stress. It is much more severe in metal microstructures than expected from macroscopically known behavior. The creep in Al thin films is so large that aluminum cannot be used as a structural mirror beam material but instead Al compounds are being used such as Al_3Ti, AlTi, AlN. These compounds have fewer primary slip systems than Al and much higher melting point. A high melting point metal often has low creep. Macroscopically, creep is non-existent as long as temperature is kept below 0.3 times the melting temperature of the material and the mechanical stress in the material is not extreme [8]. Although macroscopic laws do not apply to micro domain, the creep behavior follows the basic rule that higher melting temperature results in higher creep resistance near the room temperature. Since it is obvious that temperature affects the lifetime of the micromirror device, thermal management is very important. In order to keep temperature in the device within the acceptable range, heatsinks are being used. Adequate thermal management significantly influences lifetime of the device allowing the mirrors to be efficiently controlled over a long period of time.

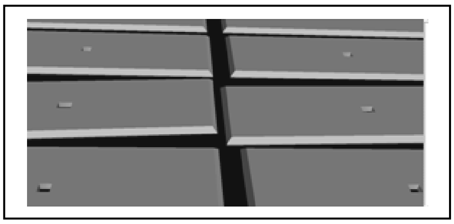

Figure 4. Schematic presentation of the hinge memory failure mode

D. Environmental Robustness

Environmental robustness is a great reliability concern for all MEMS devices. Examination of micromirror environmental robustness is based on standard semiconductor test requirements such as temperature cycling, thermal shock, moisture resistance, ESD, cold and hot storage life, etc. When MEMS are in question, a large reliability concern is vibration [9]. Due to the sensitivity and fragile nature of many MEMS, external vibrations can have disastrous implications. They may cause failure through inducing surface adhesion or through fracturing device support structures. Long-term vibration can also contribute to fatigue. Another issue can be shock. Shock is a single mechanical impact instead of a rhythmic event. A shock creates a direct transfer of mechanical energy across the device. Shocks can lead to both adhesion and fracture. Although micromirror arrays seem fragile due to their small size, their size proved to be one of their greatest assets. Small size enables their robustness. They proved to be able to sustain low-frequency vibrations and mechanical shock without mirror damage. However, besides being an asset, size of the array may be related to the another type of failure mechanism. Dimensions of MEMS micromirrors are so small that the presence of the smallest particle during fabrication may cause non-functionality of one or more devices (Figure 5).

MEMS micromirror arrays are being produced in exactly the same way as sophisticated electronic devices. The source of each contaminating particle should be detected and eliminated, especially during packaging, because particles sealed in the package may affect operation of the device during its lifetime. Because MEMS micromirror arrays interact with the environment in a certain way, they require hermetic packaging that can provide adequate protection, electronic contacts and window transparent to light. Also, vacuum packaged arrays eliminate effects of capillary stiction. Failure of moving MEMS structures due to contaminations introduced during packaging is the most common failure mode of MEMS micromirror arrays.

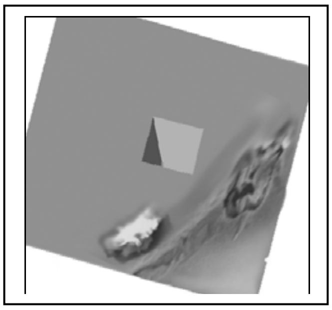

Figure 5. Schematic presentation of micromirror failure caused by particle contamination

III. CONCLUSION

A brief insight in reliability of MEMS micromirror devices has been presented in this paper. Four major reliability issues have been discussed: stiction, fatigue, hinge memory and environmental robustness. Production of reliable micromirror device requires sophisticated design considerations and better control of microfabrication processes that are used in production and packaging of MEMS device. Reliable package must not prevent mechanical action of moving parts of the structure, but it should prevent transfer of heat, moisture, outgassing, etc. Another important issue is the need for credible testing techniques applicable during fabrication, assembly and packaging as well as during the operational life of the device. It should be pointed out that industrial standardization of MEMS technology is at least several years away [10] and till then MEMS micomirror devices (as well as other types of MEMS devices) will be custom made according to customer requirements. The lack of information flow as well as the reluctance in sharing experience will keep MEMS micromirror arrays away from full commercialization although there are few commercially successful applications.

ACKNOWLEDGEMENT

Authors are grateful for the partial support of the Ministry of Education, Science and Technological Development of Republic of Serbia (contracts III44003 and III45007).

REFERENCES

[1] M. Hanf, S. Kurth, D. Billep, R. Hahn, W. Faust, et al., "Application of micromirror arrays for Hadamard transform optics", Proc. SPIE 5445, Microwave and Optical Technology 2003, 128 (April 7, 2004); doi:10.1117/12.558419

[2] U. Krishnamoorthy, K. Li, K. Yu, D. Lee, J.P. Heritage and O. Solgaard, "Dual-mode micromirrors for optical phased array applications", Sensors and Actuators A: Physical, Volumes 97–98, April 2002, pp. 21–26.

[3] S. Li, J. Xu, S. Zhong and Y. Wu, "Design, fabrication and characterization of a high fill-factor micromirror array for wavelength selective switch applications ", Sensors and Actuators A: Physical, Volume 171, Issue 2, November 2011, pp. 274–282.

[4] R. Hoskinson, S. Hampl and B. Stoeber, "Arrays of large-area, tip/tilt micromirrors for use in a high-contrast projector", Sensors and Actuators A: Physical, Volume 173, Issue 1, January 2012, pp. 172–179.

[5] Z. Stanimirović and I. Stanimirović: „Mechanical Properties of MEMS Materials", in: K. Takahata, Ed., Micro Electronic and Mechanical Systems, In Tech, 2009, Chapter 11, pp. 177-184.

[6] I. Stanimirović and Z. Stanimirović: „Reliability of MEMS", in: K. Takahata, Ed., Micro Electronic and Mechanical Systems, In Tech, 2009, Chapter 12, pp. 165-176.

[7] C.-P. Chang, "Optical MEMS Technology for Telecommunication", Proc. of 7th International Conference on Solid-State and Integrated Circuits Technology, vol. 3, pp. 1981-1986, 2004.

[8] W. Merlijn van Spengen, "MEMS reliability from a failure mechanisms perspective", Microelectronics Reliability, vol. 43, pp. 1049-1060, 2003.

[9] T.-R. Hsu: "Reliability in MEMS Packaging", Proc. of International Reliability Physics Symposium, San Jose, California, March 26-30, 2006.

[10] T.-R. Hsu: "Introduction to Reliability in MEMS Packaging," Proc. of International Symposium for Testing and Failure Analysis, San Jose, California, November 5, 2007.