Reliability Issues In Micro-Electro-Mechanical Systems

Xavier J. R. Avula

Intelligent Systems Center
Department of Mechanical and Aerospace Engineering and Engineering Mechanics
University of Missouri-Rolla
Rolla, Missouri 65409-0050 U.S.A.
Ph: (573)-341-4585 Email: avula@umr.edu or avula@acm.org

ABSTRACT

The interdisciplinary field of micro-electro-mechanical systems (MEMS) has emerged as a dominant field with potential for the development of commercially viable products such as sensors and actuators, automotive and aerospace electronics, computer peripherals, communication devices, biomedical electronics and residential controls, etc. This paper addresses some of the reliability issues associated with fabrication and performance of these products. Production and maintenance of high quality MEMS products are important for capturing a significant share of the global market which is projected to reach $15 billions by the year 2000.

INTRODUCTION

Recent advances in micro-electronics, optics, materials science and fabrication techniques have paved the way to the development of new products with new capabilities hither to unrealizable with traditional engineering. The phenomenal growth of micro-electro-mechanical systems (MEMS) in this decade indicates that the field has sufficiently developed to be of concern with the quality of products and expansion of markets.

While considerable attention has been paid to the development of MEMS concepts, fabrication techniques and systems integration methodologies, not much attention has been accorded performance evaluation and reliability of MEMS devices. With commercial and defense sectors poised to commit huge financial resources to the use of sensors, actuators, and communication products, it is imminent that we seriously consider reliability issues facing the MEMS industry.

CHARACTERIZATION OF RELIABILITY

A failure of a MEMS component or system occurs when it fails to perform its expected function. Poor reliability is generally due to failures accentuated by environmental and operational stresses. In situations where redundancy and repair are impractical, reliability is the most important indicator of quality.

Reliability based on failure mechanisms under thermomechanical load cycling has been addressed rather extensively in microelectronics in a traditional engineering sense by relating aging and performance degradation at extreme temperatures to failure rate. In MEMS, however, in view of the moving parts present in the system and novel fabrication techniques followed, one must address other issues such as failures due to fatigue cracks, and those that creep into the system during fabrication. Electromagnetic parameter changes also contribute to certain types of failures. In addition to mechanical and thermal stresses, failures due to electrical stresses, dipole interaction energy, electron tunneling phenomenon, impact ionization, charge trapping, etc. must be considered.

The constitutive relations generally believed to hold for materials used in traditional engineering devices do not hold for those of micro-dimensions. For example, the Young's modulus and Poisson's ratio for materials at microlevel will not be the same.

MATHEMATICAL CONCEPTS

Reliability is conceptually understood as the probability of a device performing a task over a stated period of time for which it is designed and fabricated. Quantification of reliability in terms of probability involves statistical methods because of the uncertainties associated with the useful life of a product. Because the sources of these uncertainties are both human and material, the statistical treatment has to deal with the behavior of the device or product resulting from an unlikely interaction of parameters that perhaps is not well understood. This is specially true in the case of MEMS for which reliabilty studies are not extensively performed. However, there are several mathemnatical concepts which are common to most engineered products. These concepts are briefly discussed in this section.

Probability. In the computation of reliabilty the concept of probabilty stands out prominently. For example, if a MEMS device of N samples alre subjected to a conventional test and n(s) number of samples are deemed successful and n(f) are failures,

the probability of survival is given by

$$p(f) = \frac{n(f)}{n} \quad (1)$$

$$p(s) = \frac{n(s)}{n} \quad (2)$$

Because the device either survives are fails, it follows that

$$p(f) + p(s) = 1 \quad (3)$$

The concept of probabilty can be easily extended to devices with multiple components and to systems consisting of multiple devices. The reader is advised to refer to other sources of information on probablity and statistics when dealing with more complex configurations of MEMS systems.

Probability density function (p.d.f.). The probability density function f(x), when integrated between 0 and x, yields the fraction of the population of devices that fails (or survives) in the interval 0 to x. Alternately, p.d.f. is the rate of failure (or survival) of the original number of devices tested in the same interval. Which can be mathematically expressed by

$$F(x) = \int_0^x f(x)\mathrm{d}x \quad (4)$$

$$f(x) = \frac{\mathrm{d}F(x)}{\mathrm{d}x} \quad (5)$$

A probability distribution function is characterized by four aspects: (a) The *central tendency* about which the distribution is grouped, (b) The *spread* which indicates the extent of variation about the central tendency, (c) The *skewness* which indicates the lack of symmetry about the central tendency, and (d) The *peakedness* which indicates the height of the distribution.

The central tendency is measured by mean, median and mode. For a sample containing n items in a larger population the sample mean is denoted by $\overline{x}$ which is given by

$$\overline{x} = \sum_{i=1}^{N} \frac{x_i}{n} \quad (6)$$

The sample mean can be used to *estimate* the population mean. For a continuous distribution, the mean is derived by extending this idea to cover the range $-\infty$ to $+\infty$. The *estimate* of a population mean is denoted by μ. The mean is also referred to as the *average value* or *s-expected value, E(x).*

$$\mu = \int_{-\infty}^{\infty} xf(x)dx \quad (7)$$

The center of gravity of p.d.f. can be obtained from this equation. Central tendency is also characterized by the *median*, which is the mid-point of the distribution, i.e. the point at which half the measured values fall to either side, and the *mode*, which is the value (or values) at which the distribution peaks. The values of the mean, median and mode for a symmetrical distribution are the same.

The spread of a distribution is the extent to which the values in the distribution vary. In practice it is measured by the *standard deviation (SD)* σ. For a finite population N

$$\sigma^2 = \frac{\sum_{i=1}^{N}(x_i - \mu)^2}{N} \quad (8)$$

If the distribution is continuous,

$$\sigma^2 = \int_{-\infty}^{\infty} (x-\mu)^2 f(x)dx \quad (9)$$

σ^2 is the second moment about the mean. The third and fourth moments about the mean give the skewness and peakedness of the distribution.

The cumulative distribution function. The cumulative distribution function (c.d.f), F(x), gives the probability that a measured value will fall between $-\infty$ and x:

$$F(x) = \int_{-\infty}^{x} f(x)dx \quad (10)$$

Reliability functions. Among the reliability issues of MEMS we will be concerned with the probability that a device will survive (no failure) in the interval (0 to x). This is the *s-reliability,* and it is given by the reliability function R(x). From this definition, it follows that

$$R(x) = 1 - f(x) = \int_x^{\infty} f(x)dx = 1 - \int_{-\infty}^{x} f(x)dx \quad (11)$$

Hazard functions. The *hazard function* or *hazard rate* h(x) is the conditional probability of failure in the interval x to (x+dx), given that there was no failure by x:

$$h(x) = \frac{f(x)}{R(x)} = \frac{f(x)}{1-F(x)} \quad (12)$$

the *cumulative hazard function* H(x) is given by

$$H(x) = \int_{-\infty}^{x} h(x)dx = \int_{-\infty}^{x} \frac{f(x)}{1-F(x)}dx \quad (13)$$

The binomial distribution. The binomial distribution describes a situation in which there are only two outcomes, such as survive or fail, and the probability remains the same for all trials. The p.d.f for the binomial distribution is

$$f(x) = \frac{n!}{x!(n-x)!}p^x q^{(n-x)} \quad (14)$$

(15)

This is the probability of obtaining x good items and (n-x) bad items, in a sample of n items, when the probability of selecting a good item is p and of selecting a bad item is q. The mean of the binomial distribution is given by $\mu = np$ and the SD is

$$\sigma = (npq)^{1/2} \quad (16)$$

The binomial distribution is discrete because it can only have values at points where x is an integer. The c.d.f of the binomial distribution (i.e. the probability of obtaining r or fewer successes in n trials) is given by

$$F(r) = \sum_{x=0}^{r} \binom{n}{x} p^x q^{(n-x)} \quad (17)$$

The Poisson distribution. The Poisson distribution can be considered as an extension of the binomial distribution in which n is considered infinite. With only one of the two outcomes (survive or fail) countable, for example, the number of failures in a given time or defects in the physical domain of a device:

$$f(x) = \frac{\mu^x}{x!}exp(-\mu) \qquad (x = 0, 1, 2....) \quad (18)$$

where μ is the mean rate of occurrence in the Poisson-distributed events. Since the Poisson distribution can represent the limiting case of the binomial distribution it gives a good approximation to the binomial distribution, when p or q are small and n is large. this is useful in sampling of MEMS devices where the proportion of defective components is low (i.e. p¡0.1).

The Poisson approximation is

$$f(x) = \frac{(np)^x}{x!}exp(-np) \quad (19)$$

(20)

$$[\mu = np; \quad \sigma = (np)^{1/2} \;=\; \mu^{1/2}]$$

The Poisson approximation referred to here allows one to use Poisson tables or charts in appropriate cases and leads to computationally simple solutions.

The normal (or Gaussian) distribution: The s-normal p.d.f is continuous and symmetric, and is given by

$$f(x) = \frac{1}{\sigma(2\pi)^{1/2}}exp\left[-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right] \quad (21)$$

Where μ is the mean. As noted earlier for a symmetric distribution the mode and the median are coincident with the mean, σ is the standard deviation, SD

In most quality control problems in industry the distribution of variations in parameters approaches a normal distribution. This observation is yet to be verified with MEMS products.

The lognormal distribution. The lognormal distribution which is also continuous is more versatile than the normal one because it offers a better fit to reliabilty data by virtue of its many shapes. In electronics industry, most observers have found that electromigration failure time distributions conform to lognormal statistics. Such a notion has not been verified in MEMS. The lognormal p.d.f is

$$f(x) = \frac{1}{\sigma(2\pi)^{1/2}} \exp\left[-\frac{1}{2}\left(\frac{\ln x-\mu}{\sigma}\right)^2\right] \quad (22)$$

Clearly the lognormal distribution is the normal distribution with lnx as the variate. The mean and SD of the lognormal distribution are given by

$$Mean \;=\; exp\left(\mu + \frac{\sigma^2}{2}\right)$$

$$SD \;=\; [exp(2\mu + 2\sigma^2) - exp(2\mu + \sigma^2)]^1/2$$

where μ and σ are the mean and SD of the natural logarithms of the data.

The exponential distribution. The exponential distribution pertains to a constant hazard rate. The

p.d.f is
$f(x) = a \ exp(-ax)$ (for $x \geq 0$)
$f(x) = 0$ (for $x < 0$)
This is an important distribution that deals with "life" statistics in reliability work in as much as the normal distribution deals with the "non-life" (hazard) statistics. As the hazard rate is often a function of time, replacing x with t, and denoting the constant hazard rate by λ, and the mean life or the mean time to failure (MTTF) by $1/\lambda$, the p.d.f is written as

$$f(x) = \lambda \ exp(-\lambda t) \tag{23}$$

The probability of no failures occurring before time t is obtained by integrating the above equation between 0 and t and subtracting from 1:

$$R(t) = 1 - \int_0^t f(t)dt = exp(-\lambda t) \tag{24}$$

R(t) is the *reliability function* (or survival probability).

The gamma distribution. In reliability work the gamma distribution addresses the situation when partial failures can exist, i.e. when a given number of partial failure events must occur before an item fails, or the time to the ath failure when time to failure is exponentially distributed. The p.d.f is

$$f(x) = \left\{ \begin{array}{ll} \frac{\lambda}{\Gamma(a)}(\lambda x)^{a-1}\exp(-\lambda x) & (\text{for } x \geq 0) \\ f(x) = 0 & (\text{for } x < 0) \end{array} \right\} \tag{25}$$

$$\mu = \frac{a}{\lambda}$$

$$\sigma = \frac{a^{1/2}}{\lambda}$$

where λ is the failure rate and a the number of partial failures per complete failure, or events to generate a failure. $\Gamma(a)$ is the *gamma function*:

$$\Gamma(a) = \int_0^\infty x^{a-1} exp(-x)dx \tag{26}$$

For a positive integer $(a-1)$, $\Gamma(a) = (a-1)!$ This pertains to the partial failure situation. The exponential distribution is a special case of the gamma distribution, when a=1, i.e

$$f(x) = \lambda exp(-\lambda x)$$

The Weibull distribution. The Weibull distribution can be used to model a wide range of life distributions generally encountered in reliabilty work related to engineering components by adjusting the distribution parameters. In terms of time t the two-parameter Weibull p.d.f is

$$f(t) = \left\{ \begin{array}{ll} \frac{\beta}{\eta^\beta} t^{\beta-1} exp\left[-\left(\frac{t}{\eta}\right)^\beta\right] & (for \ t \geq 0) \\ f(t)=0 & (for \ x<0) \end{array} \right\} \tag{27}$$

The corresponding reliability function is

$$R(t) = exp\left[-\left(\frac{t}{\eta}\right)^\beta\right] \tag{28}$$

The hazard rate is $(\beta/\eta^\beta)t^{\beta-1}$, β is the *shape parameter* and η is the *characteristic life* - it is the life at which 63.2 per cent of the population will have failed. When β = 1, the exponential reliability function (constant hazard rate) results, with

$$\eta = mean \ life(1/\lambda).$$

The value of $\beta < 1$ results in a *decreasing* hazard rate reliability function. And $\beta > 1$ in an *increasing* hazard rate reliability function. Note that the Weibull distribution approximates the normal distribution for $\beta = 3.5$.

If failures do not commence at t=0, but only after a finite time γ, then the Weibull reliability function takes the three parameter form

$$R(t) = exp\left[-\left(\frac{t-\gamma}{\eta}\right)^\beta\right] \tag{29}$$

Here γ is called the *failure-free time* or *minimum life.*

The extreme value distributions. Reliability is often concerned with the extreme values which can lead to failure. The probability density functions for maximum and minimum values, respectively, are

$$f(x) = \frac{1}{\sigma} exp\left\{-\frac{1}{\sigma}(x-\mu) - exp\left[-\frac{1}{\sigma}(x-\mu)\right]\right\} \tag{30}$$

$$f(x) = \frac{1}{\sigma} exp\left\{\frac{1}{\sigma}(x-\mu) - exp\left[\frac{1}{\sigma}(x-\mu)\right]\right\} \tag{31}$$

Only a few mathematical concepts which are generally appropriate for reliability work are presented in this section. Because considerable amount of reliability work on electrical and mechanical machines and microelectronics in terms of simulation and test results have been documented in reliability databases, the physical reliability parameters can be easily identified with the parameters of the probability distribution models presented here and reliability (hazard rate and failur-free life) of products under scrutiny can be predicted. Which means that we can choose the distribution and assess the results.The same cannot be said of the MEMS devices or processes because no such work has been attempted and results documented in any significant man ner. This is one of the major issues in MEMS reliability primarily because no data on failure mechanisms are adequately documented. The issues are concerned with identification of failure mechanisms in MEMS products and processes

RELIABILITY ISSUES

In order to address the reliability issues in MEMS one must understand their products and processes. The products include various types of biomedical, chemical, automotive, and environmental sensors, and sensors for machine diagnostics; actuators that may involve motors, levers, gears, valves and pumps; communications and defense equipment that deal with high density and low power mass data storage units, inertial navigation units, integrated micro-optomechanical components such as micro-mirrors and optical fibers, microfluidic systems for propellant and combustion control, advanced aerodynamic control, and electromechanical signal processing units for wireless communication, etc. The fabrication of these devices involve innovative techniques extended from process and packaging techniques used in the manufacture of integrated circuits and semiconductor devices. In recent years, a rich array of processes have emerged: bulk and surface micromachining, LIGA processes (X-ray lithography, electroforming and molding), wafer-to-wafer bonding, and epitaxial processes such as deposition of thin films and crystal growth techniques. With numerous products and fabrication techniques present in the MEMS domain, limitation on the length of this paper precludes detailed discussions addressing all the reliabilty issues. More than anything, the purpose of this paper is to provoke thoughts on reliability issues in MEMS in view of the lack of data both on processes and structural integrity.

For most MEMS components and systems reliability is assessed on the basis of quality control during various fabrication steps and on structural integrity when performing under load.

In a bulk micromachining process silicon is exposed to anisotropic etchants such as potassium hydroxide, ethylene diamine pyrocatechol, and hydrazine to fabricate structures such as beams and diaphragms used as accelerometers and pressure sensors. To make the components strong substrate doping is performed, and to make them active epitaxial layers are required. However, epitaxial quality is compromised by high substrate doping. What effect this incompatibility has on the reliable performance of the final product has not been investigated.

Surface micromachining technique is extensively used in sensor formation. In this process, a sacrificial layer is deposited on the top surface of a wafer. The material for the sensor itself, say a beam which can be used as an accelerometer, is then deposited over the sacrificial layer. In the final step, the sacrificial layer is etched away releasing the beam. Diaphragm type structures are also fabricated this way. One of the problems encountered in this process is the creation of compresssive internal stresses that might be released by high temperature annealing which in turn introduces additional heat related problems compromising the quality of the product. The effect of interaction of these various processes on the performance of the products need to be investigated.

Alternate to micromachining, or in conjunction with it, wafer bonding technique is employed to fabricate MEMS structures. This is done by electrostatic (anodic) bonding and fusion bonding for silicon-to-glass and silicon-to-silicon. The wafer assembly is subjected to high bonding temperatures which may abort the high precicion alignment required for good performance. Also matching of thermal expaansion coefficients of dissimilar materials is necessary for producing a high quality products. Deviations from desirable alignment and mismatch in thermal coefficiants are possibly the sources failure. Mechanical failure due to inclusions on the interface or dislocation arrays near bimaterial interface between the wafer and the substrate is another source for unreliable performance.

In LIGA processes an appropriate source of X-Ray radiation is required. The X-Ray radiation has a tendency to produce radiation hardening in materials. No data on the effect of radiation hardening on MEMS structures has been generated to date.

During operation of MEMS devices, high voltage stress generated traps in thin silicone oxides could lead to time-dependent dielectric breakdown. Stressing of dielectrics is a significant reliabilty issue.

Mechanical stresses under extreme loads and fatigue under cyclic loading are important issues in MEMS. No extensive studies have been reported on these aspects. Parameters to be monitored should bee identified for assessing performance degradation or structural failure.

To estimate device reliability in shorter time, accelerated testing is performed. The usefulness of accelerated testing has not been established for MEMS components. Care must be exercised not to introduce unrealistic failure modes in determining the reliability. Extenssive studies are required in this direction.

Life of interconnects has a direct bearing on the reliability of devices. Effect of load cycling and chemical composition must be investigated to assess the reliability.

For products fabricated by surface micromachining, etching, or deposition, there is no adequate documentation of failure mechanisms to test their reliability as this is an emerging technology. Current tests are in the frame work of military and automotive standards which may not be applicable to MEMS technology. Determination of failure mechanisms is one of the major challenges.

REFERENCES

[1] K.D. Wise, Micromechanical sensors, actuators aand systems, DSC Volume 32, ASME 1991.

[2] A. Christou, Reliability of Gallium Arsenide MMICs, John Wiley & Sons, West Sussex, U.K., 1992.

[3] P.D.T. O'Connor, Practical Reliability Engineering, Third Edition, John Wiley & Sons, Chichester, U.K. 1991.

[4] J.W. McPherson and D.A. Baglee, Acceleration factors for thin gate oxide stressing, IEEE International Reliability Sympsium, pp. 1-5, 1985.

[5] B. Schlund, C. Messick, J.S. Suehle and P. Chaparala, A new physics-based time-dependent dielectric breakdown, IEEE Annual International reliabily Physics, pp. 84-92, 1996.

[6] P. Lall, M. Pecht,and E. Hakim, Influence of Temperature on Microelectronics and System Reliability: A Physics of Failur Approach, CRC Press, Boca Raton, 1997.

[7] Y.H. Lee, K. Wu, N. Mielke, L.J. Ma, and S. Hui, Via delamination - a novel electromigration failure mechanism, IEEE Annual International Reliabilty Physics, pp.206-210, 1997

[8] D. Krajcinovic and S. Mastilovic, Some fundamental issues of damage mechanics, Mechanics of Materials, Vol. 21, pp. 217-230, 1995.

[9] V.A. Lubarda, Energy analysis of dislocation arrays near bimaterial interfaces, Int. J. Solids Structures, Vol. 34, No. 9, pp.1053-1073, 1997.

[10] K. Sakakibara, N. Ajikaa, M. Hatanaka and H. Miyoshi, A quantitative analysis of stress induced excess current (SIEC) in SiO_2 films, IEEE Transactions on Electron Devices, pp. 100-107, 1996.