COMMERCIAL-OFF-THE-SHELF
MICROELECTROMECHANICAL SYSTEMS

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ABSTRACT

Research and development of microelectromechanical systems (MEMS) has shown a significant promise for a variety of commercial applications. For example, accelerometers are widely used for air bag in automobile, MEMS inkjet print heads are used for printers, gyroscopes for guidance and navigation and pressure sensors for various industrial applications. Some of the MEMS devices have potential to become the commercial-off-the-shelf (COTS) components. Aerospace requires more sophisticated technology development to achieve significant cost savings if they could utilize COTS components in their systems. This paper provides an overview of the status of MEMS packaging technology and identifies a need for a systematic approach for this purpose.

Keywords:

Commercial-Off-The-Shelf, COTS, Microelectromechanical Systems, MEMS, Quality Assurance, Reliability, Pressure Sensors, Accelerometer, and Space Environment.

INTRODUCTION

Integrated circuit packaging and their testing is well advanced because of the maturity of the IC industry, their wide applications, and availability of industrial infrastructure. [1,2] This is not true for MEMS with respect to packaging and testing. It is more difficult to adopt standardized MEMS device packaging for wide applications although MEMS use many similar technologies to IC packaging. Packaging of MEMS devices is more complex since in some cases it needs to provide protection from the environment while in some cases allowing access to the environment to measure or affect the desired physical or chemical parameters. Microscopic mechanical moving parts of MEMS have also their unique issues. Therefore, testing MEMS packages using the same methodologies, as those for electronics packages with standard procedures might not always be possible especially when quality and reliability need to be assessed.

MEMS package reliability depends on package type, i.e. ceramic, plastic, or metal, and reliability of device. The MEMS device reliability depends on its materials and wafer level processes and sealing methods used for environmental protection.

MEMS Device Level Reliability Issues

MEMS devices are usually fabricated at microscopic level. A typical device level process flow before packaging involves surface micromachining or bulk micromachining of wafers, formation of desired pattern along

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with various bonding techniques followed by subsequent interconnection and cavity sealing in package enclosure. Surface micromachining is a technique for fabricating three dimensional micromachined structures from multilayer stacked and patterned thin films. [3-6] In bulk micromachining, a bulk of wafer is wet or dry etched to fabricate micromachined structures in either silicon crystal or deposited or grown layers on silicon. Bonding is another key process that is used during the fabrication which include field assisted thermal bonding, thermal fusion bonding, eutectic bonding, etc.

Reliability of surface micromachined device depends on materials used and processes employed to build-up by thin film processing, etc. Generally, there are large residual stresses induced in thin films that affect the performance of device to a variable degree. For example, residual stresses in thin film with improper adhesion could cause delamination. [7-9]

Bulk micromachined devices have their own unique reliability issues. These include sharp corners from anisotropic etching, adhesion issues as discussed above and generally poor quality due a nonoptimized process from many process steps. [8] In contrast, polymer micromachined devices show very high bond strength and low residual stresses. Reliability issues include poor mechanical strength, inability to perform hermetic seals, and use under high vapor pressure. An example of this technology is LIGA (Lithographie, Galvanoformung, Abformtechnik) which stands for lithography, electroplating, and molding that enables the structure of bulk micromachining with feature characteristics of micromachined devices. [5]

Different bonding techniques are used for microsensors attachment each with their unique characteristics. For example, glass to silicon joining can be accomplished by field assisted thermal bonding also known as anodic bonding, electrostatic bonding, or the Mallory process. [10] Anodic bonding has the advantage of being a lower temperature process with a lower residual stress and less stringent requirements for the surface quality of the wafers. In silicon fusion bonding, no intermediate layers needed, therefore it simplifies device fabrication. [11] Although eutectic bonding was demonstrated [12] in bare silicon against gold covered silicon, or gold covered silicon against gold-covered silicon, there are some considerable disadvantages associated with Au/Si (gold/silicon) eutectic bonding. It is difficult to obtain complete bonding over large areas and native oxides prevent the bonding to take place. Eutectic preform bonding is reported to introduce substantial mounting stress in piezoresistive sensors, causing long-term drift due to relaxation of the built-in stress. [4,5]

After wafer bonding process and interconnection, MEMS devices are generally hermetically sealed within a package. [4,5] The hermeticity is important for physical protection and in some cases for the device performance. For example, damping characteristics of a resonator in a pressure sensor is critically dependent on a good hermetic seal. In addition, the vacuum reference of an absolute pressure sensor, and the cavity of a pneumatic infrared sensor and microgyro package are all critically dependent on a good hermetic seal package. Minami et al, [13] used nonevaporable getters built into the microdevice to control the cavity pressure for critical damping of packaged micromechanical devices and similar approaches were proposed in. [14-17] Organic materials are not good candidate materials for hermetic packages. For almost all high-reliability applications, the hermetic seal is made with glass or metal. Silicones do not act as a moisture barrier; the exact mechanism by which they protect the die when applied, as a surface coat that is not yet well-understood. [18]

Reactive sealing and sealant films are other methods with highest performance characteristics especially for sealing process for pressure sensors. Recently, the first commercial absolute poly silicon pressure sensor, incorporating a reactively sealed vacuum shell, was introduced for automotive applications. [19] Another application of the sealed surface shells is the vacuum packaging of lateral surface resonators. Most resonator applications share a need for resonance quality factors from 100 to 10,000. However, the operation of comb-drive microstructures in ambient atmosphere results in low quality factors of less than 100 due to air damping above and below the moving microstructure. Vacuum encapsulation is thus essential for high Q applications. [20]

***MEMS* Packages** [21-23]

Packaging of MEMS similar to IC technologies need environmental protection, electrical signal conduit, mechanical support, and thermal management paths. Packaging redistributes electrical signal paths from tight pad dimensions to over larger and more manageable interconnection leads. The mechanical support provides rigidity, stress release, and protection from the environment. Power distribution also needs to be taken into account for optimum packaging scheme. Thermal management is needed to support adequate thermal transport to sustain operation for the product lifetime. [24,25]

Packaging of MEMS is considerably more complex as they serve to protect from the environment, while, somewhat in contradiction, enabling interaction with that environment in order to measure or affect the desired physical or chemical parameters. A package must also provide communication links through optimum interconnect scheme, remove heat through suitable selection of heat sinks, and provide robustness in handling and testing. The materials used for package should be selected to withstand not only handling during assembly and testing, but also throughout the operational environment of the product. Its robustness must be proven in terms of mechanical and thermal shocks, vibration, and resistance to chemical and other conventional life cycling tests especially needed for space applications. [26,27]

The package must also be capable of providing an interior environment compatible with any particular constraints that may affect device performance and reliability. For example, a resonator might need a good vacuum for its operation and packaging scheme need to provide such requirement. MEMS can be integrated with associated electronics on the same chip to produce better electrical output. Integration can be done in the same wafer level or through wafer bonding or utilizing multichip module carriers. [4,5,23]

Numerous papers published in literature regarding MEMS packaging issues. For example, Mallon et al., [28] has provided an overview of packaging techniques for silicon sensors and actuators and Frank et al, [29] has provided detailed overview of the packaging tools that are required for sensors. Madou [30] has discussed a variety of process issues associated with the packaging of MEMS. Senturia and Smith [31] have highlighted the importance of system partitioning, package design and process optimization when building the electronic components and sensor structures as part of the single device. Reichl [32] have described the requirements for packaging technologies, bonding techniques, chip-substrate interconnection techniques, and alternative chip integration techniques to deliver reliable, economical, and application specific solutions by choosing optimized technologies and appropriate materials combinations.

Kim [33] has described packaging scheme of pressure sensor arrays utilizing multi-chip modules and tape automated bonding (TAB) carrier. This one was developed specially for aerospace and aircraft applications thus requiring thin profile packaging with high accuracy.

Schmidt [4] has described the advantages of wafer-to-wafer bonding to realize tremendous savings in cost since this enables this packaging of a multitude of sensors or actuators simultaneously, eliminating costly individual chip-packaging steps and enhancing the higher performance.

Weiller et al., [22] have developed a spaceflight testbed for chemical mcirosensors and microsystems designed to fly on the space shuttle. The sensors integrated into this experiment include a micromachined interferometer for carbon dioxide detection, a palladium-based sensor for hydrogen, a micromachined micro hot plate sensor for carbon monoxide, and micromachined strain gauge pressure sensor, and networkable digital thermometers.

MEMS Reliability [8,9,34-36]

Reliability requirements for various MEMS will be significantly different from one application to another especially where the systems incorporating MEMS components are unique. Standardized reliability testing is not possible until common set of reliability requirements is developed. Literature survey on MEMS reliability issues produced limited information but valuable results.

Romig et al, [37] identified a list of packaging reliability concerns for microsystems. Factors mentioned that affect the MEMS packaging included tribological behavior, contamination, cleaning stiction, and typical mechanical fatigue issue. [38,39] Brown et al, [40] reported characterization of MEMS fatigue on polysilicon. Reliability assessment for media compatibility for a gas sensor produced coating requirements [41] while a need for new device passivation and alternative chip mounting techniques was identified by Dyrbye et al. [42]

Miller et al, [43] reported reliability testing of surface micromachined microengine whose analysis concluded the prevailing failure mode was the gear sticking to the substrate or to the hub and showed that significant portion of the microengine failure was infant mortality. [36,38] In another paper, Tanner et al, [44] observed a large amounts of debris in the areas of microengine rubbing which led to the failure of drive gears. They have also presented qualitative and predictive model for actuator reliability. In their recent study, the effect of moisture content on failure by wear mechanism was determined. It was shown that as the humidity decreased the volume of debris generated increased. For the higher humidity levels, the formation of surface hydroxides considered to act as a lubricant resulting in lower amounts of wear debris. [45] Patton et al, [46] also showed the effect of humidity on failure mechanism for MEMS electrostatic lateral output motor. Electrical performance degraded with increased humidity whereas mechanical seizure showed mixed results. At a very low and high humidity, failure occurred mechanically and electrically, respectively, whereas improvement observed below and above 40% RH. Kelly et al, [47] have described the issues how packaging influence the reliability and performance characteristics of MEMS.

Kohler et al., [26] have discussed the strategy towards bond qualification in silicon microsystems by using Weibull statistical approach. The results have shown that the degradation of fracture toughness in bonded microsystems during vibration and thermal cycling.

Lyke j21] has emphasized the importance of packaging in realizing the efficiencies promised by the MEMS devices. Packaging must provide the environment necessary to sustain the proper operation of MEMS devices. For almost all MEMS designs, fabrication of an integrated design, while meeting the requirement of MEMS device release chemistry is challenging.

Connelly et al., [27] have described inertial MEMS sensors development for space applications. Inertial sensors represent the important segment of an emerging MEMS technology. Draper labs have been developing miniaturized micromachined gyroscopes and accelerometers for over 10 years. Draper has transitioned this technology under an alliance agreement with Boeing. Boeing is now in pilot production to meet the automotive market demand.

JPL has been very active in MEMS characterization and their implementation for aerospace applications. For example, an extensive reliability testing of MEMS devices especially for space applications was done by Muller et al, [48] who provided a comparison for testing environments for space applications with automotive environment. Tang et al, [49] have described extensively on design, fabrication, and packaging of a silicon MEMS vibratory gyroscope for microspacecraft applications. Miller et al, [50] have described an overview of MEMS development for micro- and nano-spacecraft application and emphasized the reliability, packaging, and flight qualification methodologies that need to be developed for MEMS to produce robust MEMS for space applications. Hartley [51] discussed the requirements of a nano-g accelerometer developed by NASA in collaboration with Northeastern University for the tri-axial measurement of orbital drag on the Shuttle and Space Station. It required an acceleration range of 10-2 to 10'8 g over a frequency range of 0.00125 Hz.

COTS MEMS APPLICATIONS

The maturest MEMS devices are pressure sensors and accelerometers. The manifold absolute pressure (MAP) sensor has been used in automobile industry since 1979. [52] Today many automobiles have one of these sensors in their electronic engine control system. Pressure sensors also widely used for medical invasive blood pressure sensor applications. Accelerometer is being used for an airbag crash sensor in automobile since 1990. In addition to significant mass reduction, the integration of diagnostic characteristics into sensors, enable device internal failure detection.

Micromachined accelerometer includes mechanical flexure-supported masses and assembled sensors. The sensor is assembled via integration and then in a closed-rigid package. The sensor consists of a set of fixed beams and a moveable beam structure to sense relative movement. The beam to beam closeness could cause stiction. Hartzel et al, [53] developed a methodology for prediction of stiction-related field failures.

Spangler [54] presented development of IC package for micromachined accelerometer for automotive applications. In their recent developmental activities, the use of surface mountable package rather than single in line through package (SIP) was engineered. The surface mountable device (SMD) version gave more life to the existing die product and at the same time, that has met requirements for surface mount components.

MEMS RELIABILITY AND KEY FAILURE MECHANISMS [4-9,16,17,23-24,26-27,34-36,38]

Almost all cited reliability-testing issues were summarized for a certain application and cannot usually be used for any other application to benchmark. Understanding of MEMS reliability and technology assurance issues are key to their wider acceptance towards high reliability applications as well as technology transfer their commercialization. MEMS reliability is one of the most difficultquestions to answer since they are still in their infancy,developed for specific applications, and reliability requirements vary and finally, which frequently depend on the user requirements. In spite of differences, similar common methodologies could be developed for assessing qualification and reliability for those with similar failure mechanisms. [22,26,22]

A critical part of understanding the reliability of any system comes from understanding the system failure behavior and their mechanisms. For IC package assembly, failure generally related to solder joint. [2] In MEMS, there are several failure mechanisms that have been found to be the primary sources. These include:

- Failure by Stiction and Wear: Contrary to solder joint failure for IC system failure, thermal cycling fatigue failure for MEMS are of less critical. Stiction and wear, however, are real concern and cause most failures for MEMS. MEMS failure may occur due to microscopic adhesion when two surfaces are come into contact which is called stiction. Microscopic separations generally induce particulate which when caught between micro parts will stop part movement. Wear due to corrosive environment is another aspect of such failure.

- Delamination: MEMS may fail more often due to delamination than IC systems since there are much wider bonding applications. For example, delamination of bonded thin film materials, and bond failures of dissimilar and similar materials such as wafer-to-wafer bonding.

- Environmentally induce failures: Failure due to thermal cycling, vibration, shock, humidity, radiation effect, etc. are commonly observed for MEMS and IC packaging systems. MEMS devices because of having additional mechanical moving parts, are more susceptible to environmental failure than their IC packaging systems.

- Cyclic mechanical fatigue: This is critical for comb and membrane MEMS devices where materials are subjected to alternative loading. Even if the load is such that it is significantly below failure, the stress can cause degradation in materials properties. For example, changes in elastic properties affect resonant and damping characteristics of beam and therefore degrade MEMS sensor outputs.

- Dampening Effect: Dampening is not critical for IC packaging, but it is critical for MEMS devices, which operate with moving parts at their resonant frequency. Dampening can cause by many variables including presence of gas in atmosphere. Therefore, good sealing is essential for avoidance of such failure.

- Packaging: Packaging and development of testing methodologies and understanding their failure mechanisms including vacuum packaging of Infrared (IR) MEMS uncooled detectors and arrays, as well as, inertial MEMS accelerometers and gyros, and radio frequency (RF) resonators are key issues in the technology development path to low cost, high volume MEMS production.

COTS MEMS PROGRAM

It is apparent that a single set of reliability testing requirements for a wide application may not be possible for evaluation of MEMS technology. However, finding a common denominator and standardized testing based on the MEMS key failure mechanisms are valuable to user community. The users can carry out then any additional reliability testing specifically needed for their applications thus minimizing the cost of new technology implementation. The standardized test methodology when developed will also reduce unclear communication between users and suppliers thus avoiding any unnecessary expenses. We consider that it will be easier to start with high volume COTS type MEMS components, which have potential for high reliability application. In addition, because of their availability and lower cost, a large number of these components can be tested to generate statistically meaningful reliability data.

JPL has initiated COTS MEMS program with the objectives of understanding quality and reliability assurance associated with implementation of this technology and help to build needed infrastructure. Similarly, to COTS IC packaging program [1,2], it is intended to form an industry-wide consortium from aerospace, military, and commercial sectors. Consortium will emphasize development of test methodologies for characterizing reliability of COTS pressure sensors and accelerometers. Both these technologies were used and being considered for high reliability applications. For example, a COTS MEMS micromachined accelerometer was used for NASA-JPL Mars Microprobe, which launched in January 3, 1999 aboard the international Mars Polar Lander. [50] A COTS MEMS pressure sensor is also being evaluated at NASA Glenn Research Center for measuring airflow of inlet compressor of a turbofan propulsion system. [55]

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REFERENCES

1. R. Ghaffarian, "Ball Grid Array Packaging Guidelines," Interconnect Technology Research Institute (ITRI), August 1998, http://www.ITRI.ori4
2. E.J. Simeus, S. Stegura, R. Smedley, I. Sterian, A. Chen, C. Quart, R. Mohabir, J. Bragg, K. Chang, M. Chan, T. Buschor, D. Norton, R. Ghaffarian and J.K. Bonner, "CSP Consortia Activities: Program Objectives and Status," Surface Mount International Proceedings, August 23-27, 1998, pp. 203-230.
3. (a) B. Stark (editor) "MEMS Reliability Assurance Guidelines for Space Applications," Jet Propulsion Laboratory Publication 99-1, Pasadena, USA, January 1999 and
   (b) K.F. Man, B.H. Stark, and R. Ramesham, "A Resource Book for MEMS Reliability," JPL D 16171 (1998).
4. M. Schmidt, " Wafer-to-wafer bonding for microstructure formation," Proceedings of the IEEE, Vol. 86, No. 8, August 1998, pp. 1575 - 1585.
5. R. Gooch, T. Schimert, W. McCardel, B. Ritchey, D. Gilmour and W. Koziarz, "Wafer-level vacuum packaging for MEMS," J. Vac. Sci. Tech., A 17(4), July/Aug (1999).
6. G. Subramanian, M. Deeds, K. Cochran, R. Raghavan, P. Sandborn, "Delamination study of chipto-chip bonding for LIGA based safety and arming system', Proceedings of the International Society for Optical Engineering (SPIE), Editors: R.A. Lawton, W.M. Miller, G. Lin, and R. Ramesham, Vol. 3880, pp. 112 -119, 1999.7. S.B. Brown, "Materials Reliability in MEMS Devices", Technical Digest, International Conference on Solid State Sensors and Actuators, Transducers, pp. 591-593 (1997).
8. R. Maboudian and R.T. Howe, "Critical Review: Adhesion in surface micromechanical Structures" J. Vac. Sci. Tech. B, vol. 15, No. 1, Jan/Feb 1997.
9. Kolpekwar A, Jiang T, Blanton RD, "CARAMEL: Contamination and reliability analysis of MicroElectromechanical layout", J MICROELECTROMECH S 8: (3) 309-318 SEP 1999.
10. W.H. Ko, J.T. Suminto and G.J. Yeh, "Bonding Techniques for Microsensors," in Micromachining and Micropackaging of Transducers, C.D. Fung, P.W. Cheung, W.H. Ko, and D.G. Fleming, Ed., Elsevier, Amsterdam, Netherlands, pp. 41- 61 (1985).

11. T.A.H.N. Suga, "A novel approach to assembly and interconnection for microelectromechanical systems," Proceedings IEEE Microelectromechanical Systems (MEMS'95) p. 413 - 418, Amsterdam, Netherlands (1995).
12. B. Hok, C. Dubon, and C. Overen, Appl. Phys. Lett., 43, 267 - 269 (1983).
13. K. Minami, T. Moriuchi and M. Esashi, "Cavity pressure control for critical damping of packaged micromechanical devices," 8th International Conference on Solid-State Sensors and Actuators (Transducers '95), Stockholm, Sweden, pp. 240 - 243, June 1995.
14. R. Ramesham, "Non-evaporable getters to maintain vacuum in sealed MEMS," NPO-20617, NASA Tech Brief Pasadena, CA (1999).
15. A. Corazza and R.C. Kullberg, "Vacuum maintenance in hermetically sealed MEMS packages," SAES Getters, Preprint, Colorado, USA.
16. Rajeshuni Ramesham, "Getters for Reliable Hermetic Packages", Jet Propulsion Laboratory Document Number - 17920, Total number of pages: 89.
17. R.C. Kullberg, "Processes And Materials For Creating And Maintaining Reliable Vacuum And Other Controlled Atmospheres In Hermetically Sealed MEMS Packages," Proceedings of the International Society for Optical Engineering (SPIE), Editors: R.A. Lawton, W.M. Miller, G. Lin, and R. Ramesham, Vol. 3880, pp. 75 - 82, 1999.
18. R.K. Tanger, "Hermeticity of Polymeric Lid Sealants," 26d' Electronic Components Conference, San Francisco, CA, pp. 361 - 367 (1976).
19. SSI Technologies, Inc., "Solid-State Integrated Pressure Sensor," 1995, SSI Technologies, Inc., Janesville, WI.
20. W.C. Tang, T.H. Nguyen and R.T. Howe, Sensors and Actuators, 20, 25-32 (1989).
21. J. Lyke, "Advanced Technologies for Co-packaging MEMS", The 2°d international Conference on Integrated MicroNanotechnology for Space Applications, Proceedings, Vol 1, April 11-15 (1999), pp. 294 - 300.
22. B.H. Weiller, P.D. Chaffee, W.M. Hansen, "The Spaceflight Testbed for Chemical Microsensors and Microsystems", The 2°d international Conference on Integrated MicroNanotechnology for Space Applications, Proceedings, Vol 2, April 11-15 (1999), pp. 53 - 63.
23. R. Ramesham, R. Ghaffarian, and N.P. Kim, "Reliability issues of COTS MEMS for Aerospace Applications", Proceedings of the International Society for Optical Engineering (SPIE), Editors: R.A. Lawton, W.M. Miller, G. Lin, and R. Ramesham, Vol. 3880, pp. 83 - 88, 1999.
24. S.L. Miller, et al., "Routes to Failure Surface Micromachined IC Sensor" 1995 IEEE International Reliability Physics Proceedings, IRPS 95, pp. 311 - 317 (1995).
25. S. Bart et al., "Design rules for a reliable surface micromachined IC sensor", 1995 IEEE International Reliability Physics Proceedings, IRPS 95, pp. 311 - 317 (1995).
26. J. Kohler, K. Jonsson, M. Jonsson, L. Stenmark, and Y. Backlund, "Space Qualification of Direct Bonded Silicon Microsystems", The 2°d international Conference on Integrated MicroNanotechnology for Space Applications, Proceedings, Vol 1, April 11-15 (1999), pp. 154 -160.

27. J. Connelly, A. Kourepenis, D. Larsen, T. Marinis, "Inertial MEMS Development for Space", The 2°d international Conference on Integrated MicroNanotechnology for Space Applications, Proceedings, Vol 1, April 11-15 (1999), pp. 522 - 534.
28. J. Mallon, J. Bryzek, J. Ramsey, G. Tomblin, and F. Pourahmadi, "Low-cost high volume packaging techniques for silicon sensors and actuators," Technical Digest, 3`d IEEE solid-state sensor and actuator workshop, Hilton Head Island, S.C., June 6 - 8, 1988.
29. R. Frank, M.L. Kniffin, and L. Ristic, Chapter 6 in Sensors Technology Edited by Ljubisa Ristic, Artech House, Boston, 1994.
30. M. Madou, "Fundamentals of Microfabrication", CRC Press, Boca Raton, NY (1997).
31. S.D. Senturia and R.L. Smith, "Microsensor packaging and system partitioning," Sensors and Actuators, 15, 221 - 234 (1988).
32. H. Reichl, "Environmental Screening of Packaging and interconnections," Environmentally Conscious Design and Inverse Manufacturing, 1999. Proceedings. EcoDesign '99: First International Symposium On, Page(s): 754 -759
33. N.P. Kim, K. Li, D.J. Kovach, C-P. Chen and M.H. Tanielian, "Smart Sensor Multi-Chip Module with Direct-Chip-Attached Micro-Electro-Mechanical System (MEMS) Devices", to be published in 1999 IMAPS Proceedings, Chicago, IL, Oct 1999.
34. K.M. Delak, P. Bova, A.L. Hartzell, D.J. Woodilla, "Analysis Of Manufacturing-Scale MEMS Reliability Testing," Proceedings of the International Society for Optical Engineering (SPIE), Editors: R.A. Lawton, W.M. Miller, G. Lin, and R. Ramesham, Vol. 3880, pp. 165 -174, 1999.
35. S. Cruzel, D. Esteve, M. Dilhan, J.Y. Fourniols, F. Pressecq, O. Puig, J.J. Simonne, "Reliability Of Microsystems Based On A Failure Mechanism Approach," Proceedings of the International Society for Optical Engineering (SPIE), Editors: R.A. Lawton, W.M. Miller, G. Lin, and R. Ramesham, Vol. 3880, pp. 148 - 155, 1999.
36. N.F. Smith, W.P. Eaton, D.M. Tanner, J.J. Allen, "Development Of Characterization Tools For Reliability Testing Of Microelectromechanical Systems," Proceedings of the International Society for Optical Engineering (SPIE), Editors: R.A. Lawton, W.M. Miller, G. Lin, and R. Ramesham, Vol. 3880, pp. 156 - 164, 1999.
37. A.D. Romig (Jr), P.V. Dressendorfer, D.W. Palmer, "High performance microsystem packaging: a perspective," Microelectronics and Reliability v 37, n 10-11, Oct-Nov 1997.
38. J.A. Walraven, T.J. Headley, A.N. Campbell, D.M. Tanner, "Failure Analysis Of Worn Surface-Micromachined Micrengines," Proceedings of the International Society for Optical Engineering (SPIE), Editors: R.A. Lawton, W.M. Miller, G. Lin, and R. Ramesham, Vol. 3880, pp. 30 - 39, 1999.
39. L.R. Larson, D. Ruben, M. Henschel, S.A. Audet, "Development Of Low-Cost Accelerometer For Implantable Pacemakers," Proceedings of the International Society for Optical Engineering (SPIE), Editors: R.A. Lawton, W.M. Miller, G. Lin, and R. Ramesham, Vol. 3880, pp. 68 - 74, 1999.
40. S.B. Brown, W. van Arsdell and C.L. Muhlstein, "Materials reliability in MEMS devices," Tranducers 97, International Conference on Solid-State Sensors and Actuators, Vol. l p.591-593, 1997.
41. S. Petrovic, A. Ramirez, T. Maudie, D. Stanerson, J. Wertz, G. Bitko, J. Matkin and D.J. Monk, "Reliability test methods for media-compatible pressure sensors," IEEE Transactions on Industrial Electronics v 45 n 6 Dec 1998. P 877-885.
42. K. Dyrbye, T.R. Brown, G.F. Eriksen, F. Gert and D. Bjerringbro, "Packaging of physical sensors for aggressive media applications" J. Micromechanics and Microengineering v 6, n 1, p 187-192, Mar 1996.
43. W.M. Miller, D.M. Tanner, S.L. Miller and K. Peterson, "A.MEMS reliability: The challenge and the promise," SAND-98-0630C; CONF-980558, 9p, 31 May 1998.
44. D. Tanner, W.M. Miller, W.P. Eaton, L.W. Irwin, K.A. Peterson, M.T. Dugger, D.C. Senft, N.F. Smith, P. Tangyunyong and S.L. Miller, "The Effect of Frequency on the Lifetime of a Surface Micromachined Microengine Driving a Load," 1998 IEEE International Reliability Physics Proceedings, pp. 26-35.

45. D. M. Tanner, J. A. Walraven, L. W. Irwin, M. T. Dugger, N. F. Smith, W. M. Miller, and S. L. Miller, Proc. Of IEEE International Reliability Physics Symposium, pp. 189-197, 1999.
46. Patton, S.T., et al, "Performance and Reliability of a New MEMS Electrostatic Lateral Output Motor," IEEE International Reliability Physics Proceedings, pp. 179-189, 1999.
47. G. Kelly, J. Alderman, C. Lyden, J. Barret, "Microsystem packaging: Lessons from conventional low cost IC packaging," Proc. Micro Mechanics Europe, Barcelona, pp. 219 - 224, October 21 -22, 1996.
48. L. Muller, M.H. Hecht, L.M. Miller, H.K. Rockstad, J.C. Lyke, " Packaging and qualification of MEMS-based space systems," Proceedings of the 9th Annual International, Workshop on Micro Electro Mechanical Systems, 1995.
49. T.K. Tang, R.C. Guiterezz, C.B. Step, V. Vorperian, G.A. Arakaki, J.T. Rice, W.J. Li, I. Chakraborty, K. Shcheglov, J.Z. Wilcox and W.J. Kaiser, The 10'h Annual International Workshop on MEMS: an Investigation of microstructures, sensors, actuators, machines, and robots: proceedings, Nagoya, Japan, pp. 500 - 505, January 26-30, 1997.
50. L.M. Miller, "MEMS for Space Applications" Proceedings of SPIE, Design, Test, and Microfabrication of MEMS and MOEMS, Vol 3680, SPIE, Edited by B. Courtois, S.B. Crary, W. Ehrfeld, H. Fujita, J. M. Karam, K. Markus, 30 March -1 April 1999, Paris, France.
51. F. Hartley, "Terrestrial Applications of a Nano-g Accelerometer, "Proceedings of Sensors Expo, Baltimore, Maryland, pp. 359-362, May 4-6, 1999.
52. R. Grace, "Automotive Applications of MEMS/MST/Micromachines," Proceedings of Sensors Expo, Baltimore, Maryland, May 4-6, 1999, pp. 351-358.
53. A. Hartzel and D. Woodilla, "Reliability Methodology for Predicition of Micromachined Accelerometer Stiction," IEEE International Reliability Physics Proceedings, pp. 202-205, 1999.
54. L. Spangler, "Integrated Circuit Package Technology for Micromachined Accelerometers," NEPCON 1999 proceedings, pp. 1007-1013, 1999.
55. F. Smith, "MEMS Total Pressure Probe Progress Report," IMAPS Southern California Symposium, May 12-13, 1999.

***Brief Biography*:**

Dr. Rajeshuni Ramesham is working as a Senior Member of Engineering Staff, Quality Assurance Section, at the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA. His present research works focus on the reliability of packaging and interconnects associated with the microelectromechanical systems applications and works on the interconnect reliability under extreme temperature conditions. He also works on the application of polycrystalline synthetic diamond for MEMS, electrochemical, electroanalytical, and corrosion resistant coating applications. His research work has addressed the fundamental issues involved in diamond processing techniques, heat dissipation techniques, and electrochemical applications of diamond. He has published over 93 refereed journal and proceedings articles and has made 63 national and international conference presentations. He has given invited presentations at the national and international conferences. He has organized and chaired MEMS sessions and the co-editor of SPIE's proceedings volume on "MEMS Reliability for Critical and Space Applications".

Dr. Reza Ghafarian has 20 years of industrial and academic experience in mechanical, materials, and manufacturing process engineering. At JPL, Quality Assurance Section, he supports research and development activities in SMT, BGA, and CSP technologies for infusion into NASA's missions. He has authored nearly 100 technical papers and numerous patentable innovations. He is a frequent speaker and chaired technical conferences including SMTA International, IMAPS, ASME, SAMPE, NEPCON, SEMI, IEEE CPMT, and IPC. He received his M.S. in 1979, Engineering Degree in 1980, and Ph.D. in 1982 in engineering from University of California at Los Angeles (UCLA).