ROMANIAN JOURNAL OF INFORMATION SCIENCE AND TECHNOLOGY
Volume **11**, Number 2, 2008, 177–191

Reliability in MEMS: Design of Gold Devices for Mechanical Fatigue Tests

G. DE PASQUALE, A. SOMÀ

Mechanical Department, Politecnico di Torino,
Corso Duca degli Abruzzi 24, 10129 Torino, Italy
E-mail: giorgio.depasquale@polito.it,
aurelio.soma@polito.it

Abstract. Design and modelling of MEMS test structures for the analysis of fatigue damage occurring in oscillating microstructures is presented. Finite Element models are realized to design specimen shapes and electro-mechanical actuation parameters. Two different structural geometries are defined to obtain both traction and shear tensile specimen actuations through the actuation of out-of-plane movable plates.

Key words: fatigue damage, MEMS, stress, gold technology, interferometric microscope.

1. Introduction

Reliability of MEMS increased its relevancy together with the spread of microdevices applications in the every day life. The functioning of microfluidic bioMEMS, for example, can have a significant impact on the vitality of patients; aerospace applications impose more stringent conditions on the performance and reliability to limit repairs and replacements, etc.

MEMS devices are actually increasing the number of internal moving parts; a few years ago the average of 10 mechanical structures per device was estimated, but this number has risen significantly with the advent of micro-mirrors that house millions of moving parts. From a statistical point of view every additional component increases the global chance of failure for the system [1]. The reliability of MEMS must be considered at three different levels:

– system reliability;

– component reliability;

– material reliability.

For example the proper functioning of a microengine (the system) is guaranteed by the functionality of micro-rotors, gears, bearings, etc. working inside it (the components); the reliability of these follows the failure mechanisms of their materials [2]. The system is related to its components through the sub-assembly design and internal interactions; component level reliability is related to material level reliability through the study of fatigue damage mechanisms for specific geometries, environmental conditions and stress levels.

Some works propose a failure model at the system level examining the propensity for various types of failure modes in the devices; [3, 4] investigate several complicated micro-engines, [5] describe a wireless strain sensing system which packaging is designed for increased reliability; parametric FEM of some technological packaging examples are described [6] focusing the attention on thermo-mechanical reliability.

1.1. Mechanical Reliability Issues

Electro-mechanical coupling often represents a crucial issue for the system reliability; also fluidic interactions (*e.g.*: with surrounding air) can determine a changing in dynamic properties of micro-resonators or inertial system with a decay of performances; many other sources of collapse are potentially involved in the reliability. By focusing the attention on the material level of failure, mechanical damage represents the more relevant source of collapse; mechanical reliability issues are concerned with:

– *mechanical fatigue*: devices as micro-mirrors or micro-switches operating at high frequencies and which motion is controlled by structural hinges or elastic suspensions suffer from cyclic fatigue damage accumulation; crack initiation and propagation take place in the material and may cause the component failure;

– *thermal fatigue*: many sensors and actuators operating by thermal actuation are subjected to relevant temperature gradients and structural strain levels resulting in thermal cycling, high temperature fatigue or creep;

– *mechanical strength*: the structural integrity of high-stressed components as micro-needles for bioMEMS or thermal posts for micro-heat exchanges is crucial to avoid fracture collapse;

– *surfaces and contact failures*: devices including surfaces that come in contact as micro-actuators with electrical actuation pads require a control on the adhesion properties; rotating structures as micro-rotors contained in micro-engines need good surface properties resisting wear and stiction.

1.2. The Device Dependency

Fatigue failure test results are usually presented in the literature in the traditional form of S-N curves; this requires a high number of failures (represented by a single point of the curve) to realize a single diagram. Another difficulty lies in the fact that the data from S-N curves also capture the device-to-device variability, affected by the uncertainties of material characteristics and fabrication processes. Frequently each investigation involving specific devices tends to be device-dependant; fabrication processes, etching techniques or the substrate material play a major role on film structure strength as well as the presence of initial defects [2, 7].

1.3. Fatigue Testing Strategies

Many studies and experiments have been performed in order to investigate mechanical fatigue properties of MEMS materials. Mechanical tests can be divided in two categories according with the experimental configuration: the *in-situ* configuration of the equipment uses on-chip testing machines with specimens that are embedded; some other experiments are conduced with an *ex-situ* configuration through macro-dimensional testing machines [1].

The first group is the more relevant in the literature and simple test structures as micro-beams and micro-cantilevers are largely used for fatigue testing. Uniaxial cyclic loading tests are performed [8] on single crystal specimens and a reduction in fatigue life is observed for specific strain levels on specimens. The fracture caused by fatigue loading on Ni-P amorphous alloy micro-cantilevers is examined [9]; fatigue strength is observed to be about one-third of the static bending strength. From the aspect of fracture striations the authors conclude that the crack propagation occurs by cyclic plastic deformation at the crack tip. A micro-cantilever specimen is used also by [10, 11]; the beam is electrically actuated to produce a cyclic loading and a load cell is used to measure the load intensity inside it. Paper [12] defines a novel actuation design to study fatigue properties of silicon nitride thin films; an ex-situ mechanical testing machine enabling fatigue analyses on microstructures is developed by [13] where single crystal Si elements are tested and fracture surfaces are analyzed by AFM.

Many fatigue experiments are performed by [14, 15, 16] on polysilicon resonant structures oscillating in-plane; a perforated plates moved by two sets of comb-drives determines the bending of a notched cantilever. A decay of fracture strength with respect to the single crystal case is documented, together with the correlation between the damage accumulation during crack initiation and the surface oxidation.

1.4. The Environment Influence on Reliability

Failure at material level is popularly investigated operating the MEMS device at its resonant frequency and observing the resonance degradation until the failure; this approach was followed by [17] on silicon cantilevers for the monitoring of crack stable growth. The influence of environmental humidity on the fatigue life is analyzed [18, 19], showing that the crack growth period is often a very small part of the total specimen life if compared to the crack initiation [18, 19, 20]. Many presented studies attribute the failure at material level to the combined effects of an active atmosphere and surface forces; a chemical reaction between the oxygen and the exposed silicon surface takes place resulting in the formation of a thin amorphous silica layer [21] that shows stress corrosion cracking [22] and causes an evolution of the surface topology during the cyclic loading [23]. A formulation of design rules for better structural design is proposed by [24] referring to cracking mechanism. Surface topology evolution during fatigue actuation of polysilicon resonating structures has been demonstrated by many other works [23, 25, 26, 27, 28] and large perturbations located where stress level is highest (*e.g.*: at the notch root) are described. The effect of water on fatigue behaviour is investigated [13] resulting in an acceleration of fatigue damage process.

1.5. The Material Influence on Reliability

At this point the importance of a well-established understanding of failure processes due to fatigue for different types of materials is evident.

At present the material used more largely for MEMS building is polysilicon; it is also the material for which the highest number of studies and experiments has been performed, leading to a first knowledge of its fatigue behaviour basics; prior experiments shown that bulk silicon does not undergo either static or cyclic fatigue because of its inability to undergo plastic deformation by slip [29, 30, 31]. This property is not present in the major part of different bulk materials as metals or metal alloys. Similarly bulk silicon does not appear to be subjected to static fatigue damage assisted by the environment [32], that normally causes chemical reactions with surfaces and crack-tip transportation in bulk material alloys.

These considerations referred to bulk materials indicate the possible existence of strong differences of fatigue damage between polysilicon and metals also at the micro-scale. A survey of the literature testified a lack of experiences in investigation of fatigue behaviour of metal microstructures. In [33] fatigue testing methods for thin metal films are summarized and described by observing the relevance of the length scale of the material on the damage with respect to bulk material; in [7] is evaluated the size effect on the mechanical response of suspended thin gold membranes and the effect of thickness on yield stress and failure of the membrane is described. The fatigue behaviour of gold micro-bridges at resonance frequency and pull-in actuation voltage is analyzed in [34] and structural stiffness and electrical resistance variations are monitored. A fatigue damage model based on critical-plane energy of crack initiation is proposed by [35] where fatigue damage accumulation is found to be oriented on inclined {111} silicon planes; results are compared with experimental tests extracted from previous works in literature.

Among the different aspects of reliability described this work presents a design procedure for the dimensioning of *"in-situ"* gold test structures; two experimental settings are developed in order to analyze the fatigue behaviour under traction and shear stress [36]. The specimen results embedded in the actuation device, represented by planes moving out-of-plane.

2. Technology

In the present paper test structures are developed through fabrication technology of the ITC-IRST Scientific and Technological Research Centre (Trento, Italy). Involved technological processes allow the deposition of many superimposed layers and the realization of gold suspended structures. Lower actuation electrodes are realized by a polysilicon layer deposited upon the substrate, which is previously oxidized on the surface; a thin later of passivation material (LTO) is then deposited over the conductor. Suspended parts are realized through a sacrificial layer (then removed) that allows the creation of a 3 μm thick air gap; testing of microstructures is provided to be performed in ambient air. Upon the spacer is deposited a single layer of gold (1.8 μm thick) for thin structures, or an additive second layer (3 μm thick) for more rigid parts.

Described technology allows the realization of movable structures only oscillating in the out-of-plane direction, determining a discrete limitation in geometry design decisions.

3. Test structures

Most important issues of the design are related to the reach of a desired tension level inside the specimen and the possibility to correctly actuate and detect specimen during the test. First problem is related with the possibility to realize different tension levels with respect to the actuation voltage into a desired range of values; these values are imposed by instruments employed for measurements. In particular, test structures are designed to be actuated through an alternate voltage at a fixed frequency to precisely counting load cycles; a current measure across the specimen is provided to monitor the progressive material damage. All measurements and direct observations will be performed by the optical interferometric microscope ZoomSurf3D (Fogale Nanotech). Second problem is connected to the working range of voltage generator of the microscope, which influences the dimensioning of parallel plates area involved in the electrical actuation.

3.1. Shear Fatigue Structure

A rectangular specimen is realized; one side is fixed to a rigid constraint, while the opposite side is connected to a movable plate electrically actuated (Fig. 1). Plate motion determines the specimen bending and a shear tension takes place inside it. An opportune connection radius is provided to avoid the notch-effect in correspondence with specimen-support and specimen-plate conjunctions. Movable plate is clamped at the extreme opposite to the specimen; a set of square holes is positioned to allow the sacrificial layer removal during fabrication processes.

When the plate is actuated it moves towards the lower electrode; thank to the high ratio between the plate length and its tip deflection, it is reasonable to assume that plate end-section rotation around its central axis is negligible; this allows assuming a perfect shear actuation of the specimen. Lower actuation electrode has the same extension of the plate. Specimen is realized by a unique gold layer, while the plate thickness is increased by the double layer superposition.

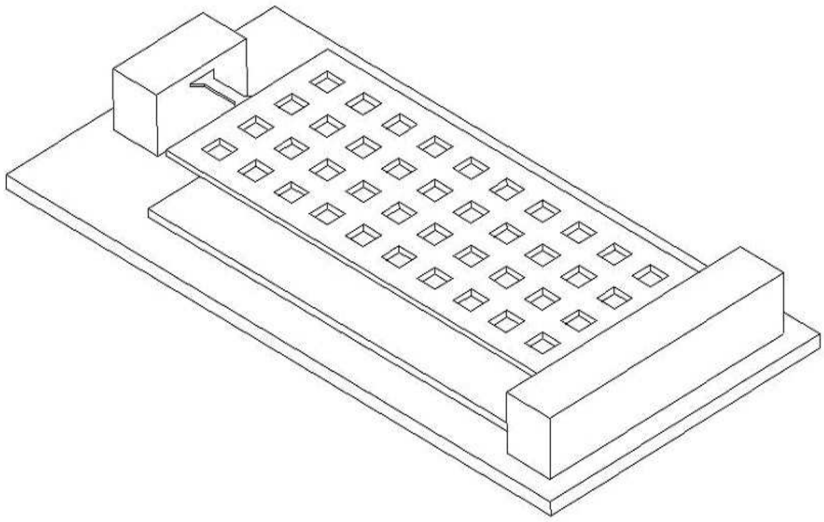


Fig. 1. Shear test structure shape.

3.2. Traction Fatigue Structure

A rectangular specimen is designed in this case too; both sides are connected to movable plates electrically actuated.

Plates are simultaneously attracted by lower electrodes and during their motion a progressive traction of the central microbeam is determined. To realize an appreciable elongation of specimen, plate length must be as small as possible in order to reduce the curvature radius of the circular motion described by plates tip. In this case electrodes have a smaller extension with respect to the plates and are externally positioned; this allows an increase of plates deflection avoiding pull-in.

To realize a sufficient actuation area, plates width is enlarged. The specimen is realized by a single gold layer, while plates present two thicker superimposed layers.

Structural constraints are crucial because it is necessary to realize a quasi-rigid rotation of plates around their clamped edge; an uncontrolled flexional deformation of plates can influence the mono-axial traction of specimen, causing the comparison of an additional flexural stress distribution inside it. A particular plate constraint is adopted to allow its rotation; at this purpose a series of four micro supports operating as cantilevers are employed. Their stiffness must be sufficient to avoid a vertical motion of the external edge of plates. Complete test structure is represented in Fig. 2; geometrical dimensions of both structures are reported in Table 1.

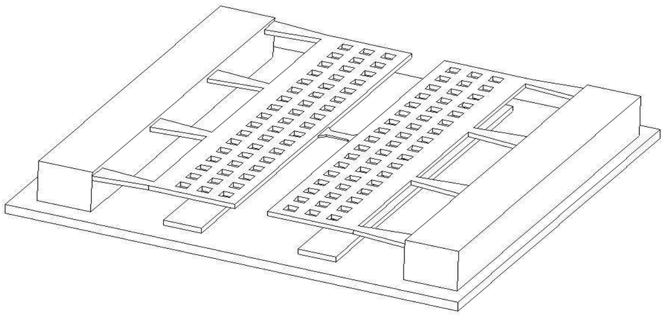


Fig. 2. Traction test structure shape.

Table 1. Test structures dimensions

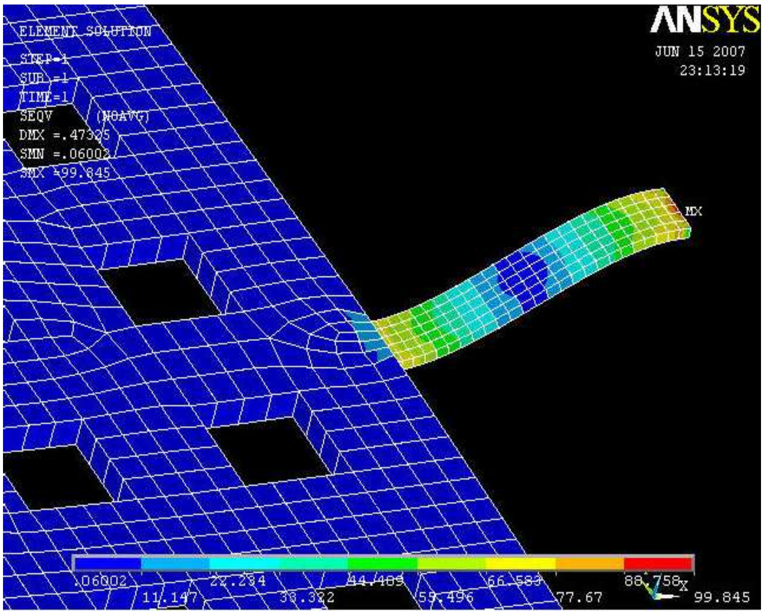
	shear structure (μm)	traction structure (μm)
specimen length	50	30
specimen width	10	10
specimen thickness	1.8	1.8
plate length	420	80
plate width	180	350
plate thickness	4.8	4.8
holes side	20	10
holes interspace	20	10
supports length	–	50
supports width	–	10–20
supports thickness	–	4.8
lower electrode length	420	35
lower electrode width	460	350
gap thickness	3	3

4. F.E.M. simulations

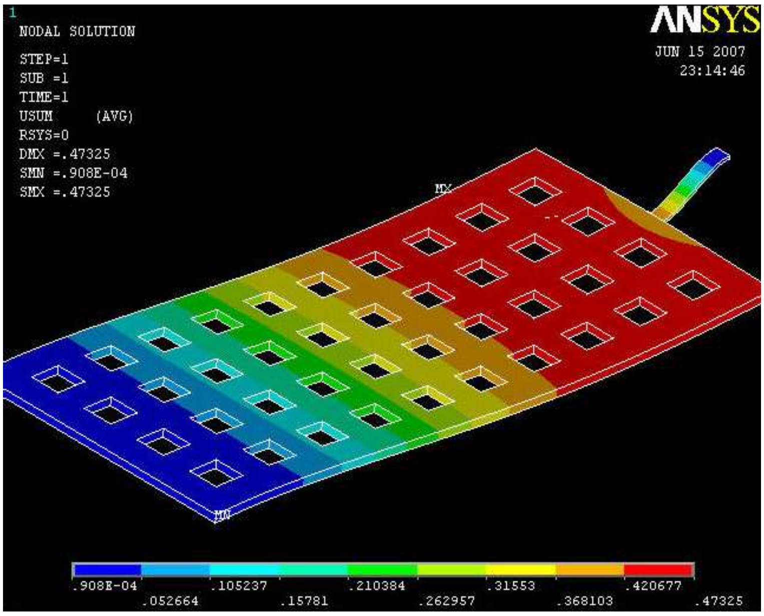
Numerical models are realized for both test structure types in order to optimize their shape and dimensions. The commercial tool Ansys 10.0 is used for simulations.

4.1. Electro-Mechanical Analysis

Electro-mechanical actuation parameters and specimens internal stress entity are controlled (Figs. 3 and 4); structural parts are modelled by tetragonal 3-dimensional elements or simpler quadrilateral 2-dimensional elements; Young modulus $E = 98.5$ GPa, Poisson ratio $\nu = 0.42$ and specific density $\rho = 19.32 \cdot 10^{-15}$kg/μm^3 are assumed. Electro-mechanical coupling is realized by proper 1-dimensional elements.



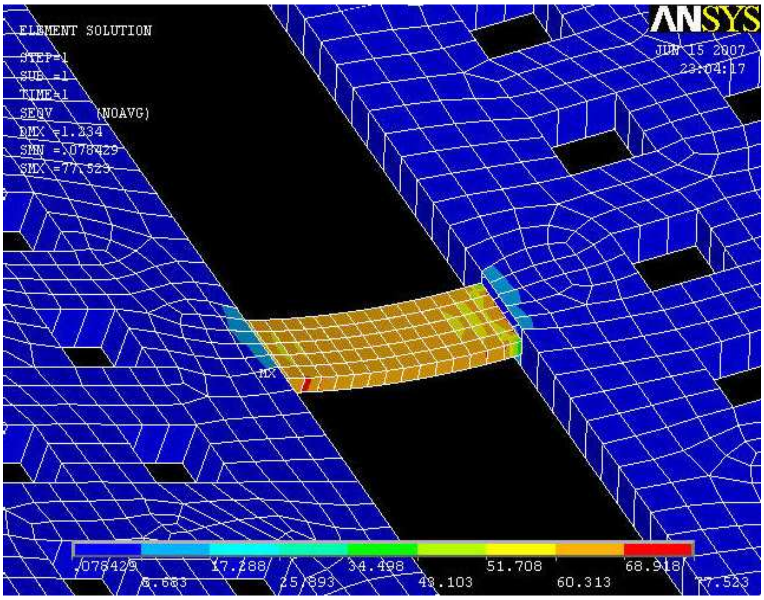
a)



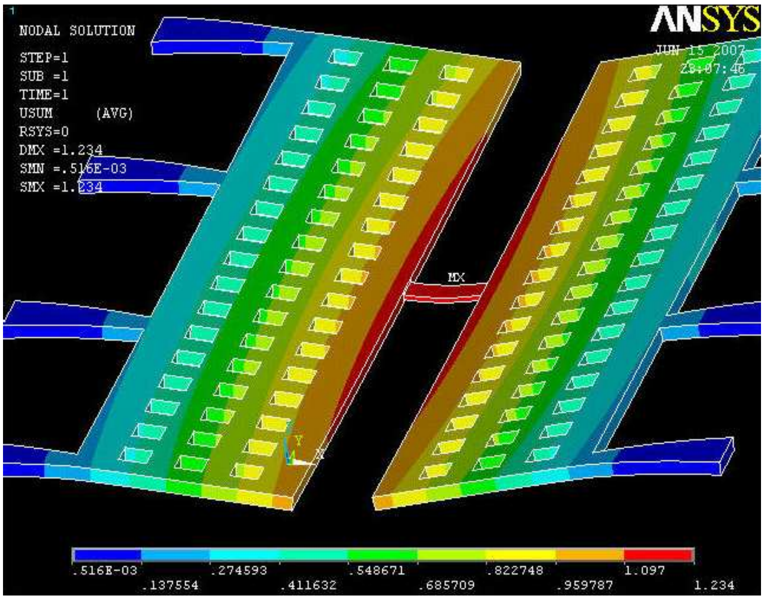
b)

Fig. 3. Von Mises stress (a) and vertical deflection (b) of shear specimen under a 45 V actuation voltage; connection radius are omitted here.

An external voltage constraint is statically imposed between plates and lower electrodes; the iterative simulation convergence is reached when structural-elastic forces equilibrate the electrical capacitive attraction. Specimen stress level is evaluated with respect to plates deflection for different actuation voltages.



a)

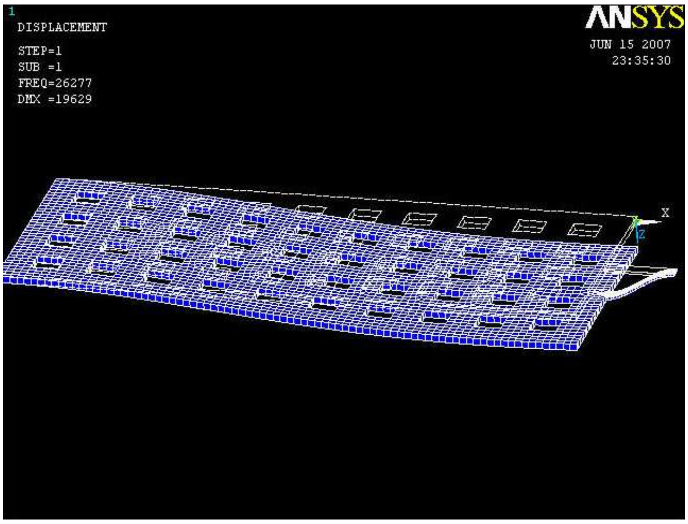


b)

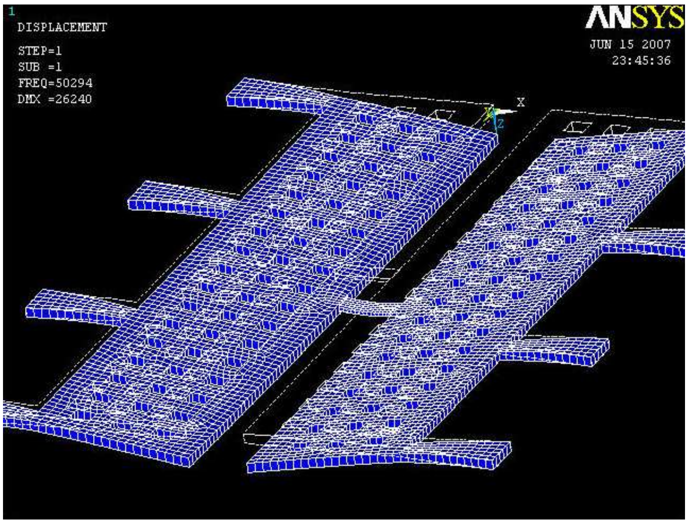
Fig. 4. Von Mises stress (a) and vertical deflection (b) of traction specimen under a 165 V actuation voltage; connection radius are omitted here.

4.2. Modal Analysis

Test structures are designed for an actuation under an alternate voltage producing a harmonic motion of plates and a cyclical loading of specimen; frequency of actuation is provided to be at least one order of magnitude lower than first resonance frequency to avoid uncontrolled amplification of oscillation amplitude with the possibility of pull-in or instantaneous mechanical collapse.



a)



b)

Fig. 5. First resonance modal shapes of shear (a) at 26.28 kHz and traction (b) at 50.29 kHz test structures.

Moreover resonance frequency values are expected to vary in consequence of progressive material damage accumulation. To detect first resonance frequency and corresponding modal shape of test structures a modal analysis is performed; first modal shapes of test structures are represented in Fig. 5.

5. Results

F.E.M. simulation results are presented in Tables 2 and 3; maximum plates vertical deflection and corresponding Von Mises equivalent stress are extracted for different static voltage values.

Table 2. Shear specimen deflection and Von Mises equivalent stress with respect to actuation voltage

Voltage (V)	Deflection (μm)	Von Mises stress (MPa)
10	0.024	4.710
20	0.095	18.84
30	0.215	42.39
40	0.382	75.37
50	0.596	117,8
60	0.858	169.6

Table 3. Traction specimen deflection and Von Mises equivalent stress with respect to actuation voltage

Voltage (V)	Deflection (μm)	Von Mises stress (MPa)
130	0.640	36.22
150	0.907	51.34
160	1.176	66.60
170	1.426	80.85
178	1.861	105.6

Figures 6 and 7 report respectively deflection and stress variations for shear test structure; figs. 8 and 9 report respectively deflection and stress variation for traction test structure.

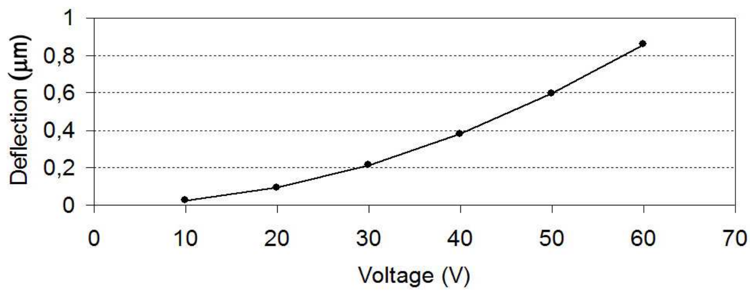


Fig. 6. Shear specimen deflection with respect to actuation voltage.

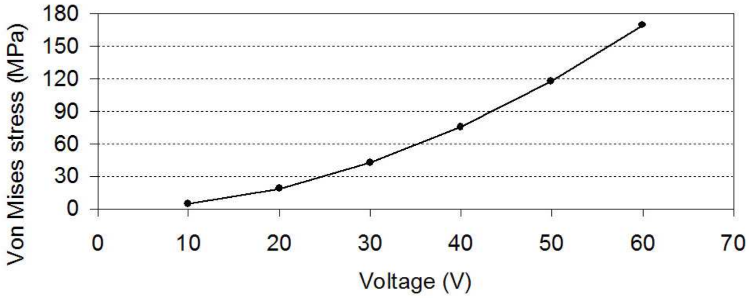


Fig. 7. Shear specimen equivalent stress with respect to actuation voltage.

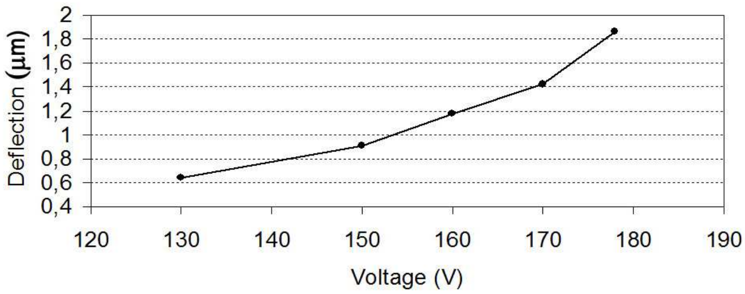


Fig. 8. Traction specimen: deflection with respect to actuation voltage.

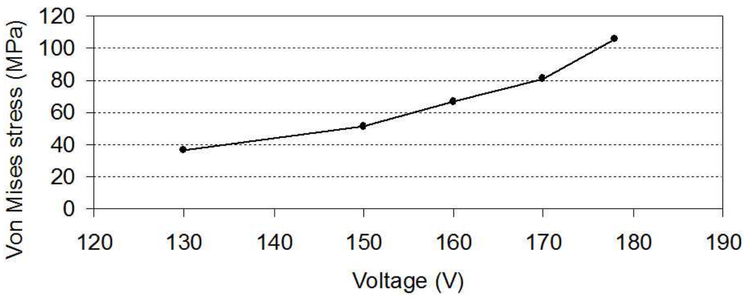


Fig. 9. Traction specimen: equivalent stress with respect to actuation voltage.

From literature [37] it is possible to determine that the static fracture tensile strength of the material is approximately 120 MPa. Figures 6–9 show that the actuation voltage from zero to pull-in value allows to perform fatigue test from very low stress level to stress level of the same order of magnitude of the static tensile strength of the material.

6. Conclusions

Shear and traction test structures for mechanical fatigue analysis of MEMS gold specimen are presented; main design issues are focused and F.E.M. models are realized to improve geometrical optimization. Electro-mechanical coupling and specimen stress gradients can be controlled with respect to actuation voltage. The designed devices allow obtaining alternate fatigue tests at different stress level.

References

[1] ALLAMEH S. M., *An introduction to mechanical-properties-related issues in MEMS structures*, Journal of Materials Science, vol. **38**, pp. 4115–4123, 2003.

[2] SOBOYEJO A. B., BHALERAO K. D., SOBOYEJO W. O., *Reliability assessment of polysilicon MEMS structures under mechanical fatigue loading*, Journal of Materials Science, vol. **38**, pp. 4163-4167, 2003.

[3] TANNER D. M., WALRAVEN J. A., HELGESEN K. S., IRWIN L. W., GREGORY D. L., STAKE J. R., SMITH N. F., *MEMS Reliability in a Vibration Environment*, Proc. IEEE International Reliability Physics Symposium, p. 139, 2000.

[4] TANNER D. M., WALRAVEN J. A., HELGESEN K. S., HELGESEN L. W., BROWN F., SMITH N. F., *MEMS Reliability in a Vibration Environment*, Proc. IEEE International Reliability Physics Symposium, p. 129, 2000.

[5] SUSTER M., GUO J., CHAIMANONART N., KO W. H., YOUNG D. J., *A high-performance MEMS capacitive strain sensor microsystem*, Journal of Microelectromechanical Systems, vol. **15(5)**, pp. 1069–1077, 2006.

[6] WUNDERLE B., AUERSPERG J., GROBER V., KAULFERSCH E., WITTLER O., MICHEL B., *Modular parametric finite element modelling for reliability studies in electronic and MEMS packaging*, Microsystem Technologies, vol. **10**, pp. 375–381, 2004.

[7] ESPINOSA H. D., PROROK B. C., *Size effects on the mechanical behavior of gold thin films*, Journal of Materials Science, vol. **38**, pp. 4125-4128, 2003.

[8] ANDO T., SHIKIDA M., SATO K., Sensors and Actuators A: Physical, vol. **93(1)**, p. 70, 2001.

[9] MAEKAWA S., TAKASHIMA K., SHIMOJO M., HIGO Y., SUGIURA S., PFISTER B., SWAIN M. V., *Fatigue Test of Amorphous Alloy microcantilever Beams*, Proc. International Microprocesses and Nanotechnology Conference '99, p. 132, 1999.

[10] SHARPE W. N., YUAN B., EDWARDS R. L., Journal of Microelectromechanical Systems, vol. **6**, p. 193, 1997.

[11] SHARPE W. N., TURNER K. T., Proc. Fatigue'99, p. 1837, 1999.

[12] CHUANG W. H., FETTIG R. K., GHODSSI R., *Nanoscale fatigue study of LPCVD silicon nitride thin films using a mechanical-amplifier actuator*, Journal of Micromechanics and Microengineering, vol. **17**, pp. 938–944, 2007.

[13] KOMAI K., MINOSHIMA K., INOUE S., *Fracture and fatigue behaviour of single crystal silicon microelements and nanoscopic AFM damage evaluation*, Microsystem Technologies, vol. **5**, pp. 30–37, 1998.

[14] MUHLSTEIN C. L., BROWN S. B., RITCHIE R. O., *High cycle fatigue and durability of polycristalline silicon thin films in ambient air*, Sensors and Actuators A: Physical, vol. **94**, pp. 177–188, 2001.

[15] MUHLSTEIN C. L., BROWN S. B., RITCHIE R. O., Journal of Microelectromechanical Systems, vol. **10**, p. 593, 2001.

[16] MUHLSTEIN C. L., BROWN S. B., RITCHIE R. O., Appl. Phys. Let., 2001.

[17] CONNALLY J. A., BROWN S. B., Science, vol. **256**, p. 1537, 1992.

[18] BROWN S. B., VAN ARSDELL W., MUHLSTEIN C. L., *Materials Reliability in MEMS Devices*, Proc. Transducers '97 International Conference on Solid-State Sensors and Actuators, vol. **1**, 1997.

[19] VAN ARSDELL W., BROWN S. B., Journal of Microelectromechanical Systems, vol. **8(3)**, p. 319, 1999.

[20] KAHN H., BALLARINI R., MULLEN R. L., HEUER A. H., Proc. Royal Soc. London A, vol. **455**, p. 3807, 1999.

[21] KOVACS G. T. A., Micromachined Source Handbook, p. 27, (McGrow Hill Ltd., 1998).

[22] THOULESS M. D., COOK R. F., Appl. Phys. Lett., vol. **56(21)**, p. 1962, 1990.

[23] ALLAMEH S. M., GALLY B., BROWN S., SOBOYEJO W. O., Surface Topology and Fatigue in Si MEMS Structures, Mechanical Properties of Structural Films, STP 1413, edited by C. Muhlstein and S. Brown, p. 1, 2001.

[24] LIU X. H., SUO Z., MA Q., FUJIMOTO H., Engin. Fract. Mech., vol. **66(4)**, p. 387, 2000.

[25] ALLAMEH S. M., SHROTRIYA P., BUTTERWICK A., BROWN S., SOBOYEJO W. O., Journal of Micro-electromechanical Systems, 2002.

[26] ALLAMEH S. M., GALLY B., BROWN S., SOBOYEJO W. O., *Surface Topology and Fatigue in Si MEMS Structures*, Proc. Mater. Res. Soc. Symposium, p. 657, 2001. Mechanical Properties of Structural Films, STP 1413, edited by C. Muhlstein and S. Brown, p. 1, 2001.

[27] SHROTRIYA P., ALLAMEH S. M., SOBOYEJO W. O., *On the evolution of Surface Morphology of Polysilicon MEMS Structures During Fatigue*, Proc. ASME Annual Meeting, 2001.

[28] SHROTRIYA P., ALLAMEH S. M., BROWN S., SUO Z., SOBOYEJO W. O., *Fatigue Damage Evolution in Silicon Films for Micromechanical Applications*, Experimental Mechanics, vol. **43(3)**, pp. 289–302, 2003.

[29] BHALERAO K., SOBOYEJO A. B., SOBOYEJO W. O., *Modeling of fatigue in polysilicon MEMS structures*, Journal of Materials Science, vol. **38**, pp. 4157–4161, 2003.

[30] SURESH S., Fatigue of Materials, 2nd ed. (Cambridge University Press, 1998).

[31] WIEDERHORN S., Fract. Mech. Ceram., p. 613, 1974.

[32] LAWN B., Fracture of Brittle Solids, 2nd ed. (Cambridge University Press).

[33] ZHANG G. P., VOLKERT C. A., SCHWAIGER R., MONIG R., KRAFT O., *Fatigue and Thermal Fatigue Damage Analysis of Thin Metal Films*, Proc. IEEE Int Conf on Thermal, Mechanical and Multiphysics Simulation and Experiments in Micro-Electronics and Micro-Systems, 2006.

[34] MILLET O., BERTRAND P., LEGRAND B., COLLARD D., BUCHAILLOT L., *An Original Methodology to Assess Fatigue Behavior in RF MEMS Devices*, Proc. 12^{th} GAAS Symposium, pp. 467–470, 2004.

[35] VARVANI-FARAHANI A., *Silicon MEMS components: a fatigue life assessment approach*, Microsystem Technologies, vol. **11**, pp. 129–134, 2005.

[36] DE PASQUALE G., SOMÀ A., *Design and finite element simulation of MEMS for fatigue test*, Proc. CAS International Semiconductor Conference '07, vol. **1**, pp. 159–162, 2007.

[37] MARGESIN B., BAGOLINI A., GUAMIERI I., GIACOMOZZI F., FAES A., *Stress characterization of electroplated gold layers for low temperature surface micromachining*, Proc. DTIP Design, Test, Integration and Packaging of MEMS/MOEMS, 2003.