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SPECIFIC METHODS USED AT TESTING OF MEMS MATERIALS

Adrian-Petru POP[1]
[1]University of Oradea, Faculty of Management and Technological Engineering, Romania,
[1]adippop@yahoo.com

Abstract—The paper presents some specific methods used at testing of MEMS materials, which impose other rules and conditions as classical materials. MEMS materials are specific properties, such as their fragility, easy damages or fractures and small size of specimen at handling and testing, which needs special technique and installations adapted these conditions. The main characteristics of MEMS materials are internal stress, Young's modulus, Poisson's ratio, fracture strength and toughness, and thermal conductivity and specific heat. The accuracy of measurements required determination of high precision of results that are affected by the specimen boundary or specimen shape, and specific approaches methods.

Keywords— Compression**,** MEMS**,** Tensile, Thin film

I. INTRODUCTION

THE MEMS materials are widely used in micro- and nano-technologies and MEMS structures offer many potential advantages as them miniaturization, which save space, energy and weight due to reduce the cost since thousands of these devices on a single wafer can be building [1]-[4].

The aim of materials used for MEMS (Micro Electro Mechanical System) is to assure the certain properties in immediately connection with them activity range and applications, but not at least with them characteristics, as mechanical, electrical, thermal, magnetic, optical and chemical. Once with micromachining development of 1980s, the materials on thin film forms won more space as mono-crystal silicon as substrate material that can be explained by the dependence of material properties on the process conditions [5]-[11].

A significant problem with these materials and parts are them very small dimensions which makes difficult to obtain them characterization and testing. At thin films with thicknesses of 100 to 1000 micrometers, these evaluations are more serious and impose specific modes of tests to avoid the fragility risks of samples at handling and testing. In this sense have been done some approaches to measure the material characteristics used for MEMS that is named "*microfabricated test structures*". By these methods can be determined differently mechanical characteristics of thin film, as [9]:

- Internal stress
- Young's modulus
- Poisson's ratio
- Yield strength
- Fracture strength
- Fracture toughness
- Fatigue

, and also thermal characteristics as:

- Thermal conductivity
- Specific heat.

II. METHODS OF TESTING USED FOR MEMS

A. Internal Stress

The internal stresses-σ or residual stresses can induce the deformations about of microstructures, each cracking into thin films. For thin films, this internal stress is constrained on the substrate of deposition of film, which can be constrained in a compressed state that named compressive and expressed as negative value, or in extended state that named tensile and expressed as a positive value. At occurrence of internal stress two major recourses are favorable, as [2], [8], [9]:

- Thermal mismatch between substrate and a thin film, which is named extrinsic stress-σ_e.
- Microscopic structural change of a thin film during deposition or post-processing led to film nucleation, which represents intrinsic stress- σ_i.

The internal stress can be determined with the Hook's Law [2], [7]-[9]:

$$\sigma = \varepsilon \cdot E \tag{1}$$

, that is applied the isometric materials with uniaxial stress, which for a biaxial stressed material as thin films the (1) becomes [2], [7]-[9]:

$$\sigma = \frac{\varepsilon \cdot E}{1-\nu} \tag{2}$$

, where: ν- is Poisson's ratio of thin film. The problem of σ-determination is resumed at found of deformation-ε while the value of Young's modulus-E is usually known. In this case, it can be approached three differently micro-test structures fabricated with surface micromachining, which assured the measure of deformation of thin film-ε, as doubly supported beam, ring and beam, and rotation beam; doubly supported beam and ring and beam patterns are complementary techniques used for measuring compressive and tensile stress. At preparation of the pattern with incrementally size is required, critical length of straight beam-L_c that caused bucking can be determined [2], [8], [9].

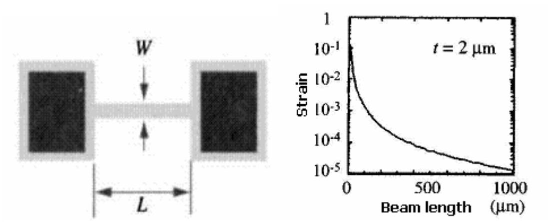

Fig. 1. Microtest structure at rotation beam for strain measurement (w = 5µm, L=10-500µm, t = 2µm) [8], [9].

For the doubly supported beam (Fig. 1), the strain-ε is calculated from the buckling length-L_c of the beam and thickness of thin film-t, using the formula [8], [9]:

$$\varepsilon = -\frac{\pi^2}{2}\left(\frac{t}{L_c}\right)^2 \qquad (3)$$

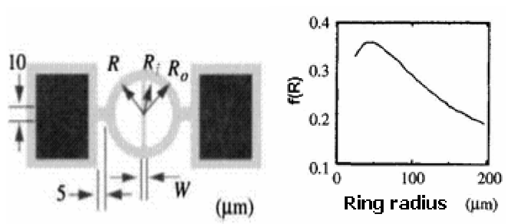

Fig. 2. Micro test structure at ring and beam for strain measurement (w = 5µm, R_0-R_i=20µm, R = 20-250µm) [8], [9].

For the ring and beam (Fig. 2), the strain-ε is calculated from the buckling radius-R_c of the center beam using the formula [8], [9]:

$$\frac{\pi^2 t^2}{48 f(R) R_c^2} \le \varepsilon \le \frac{\pi^2 t^2}{12 f(R) R_c^2} \qquad (4)$$

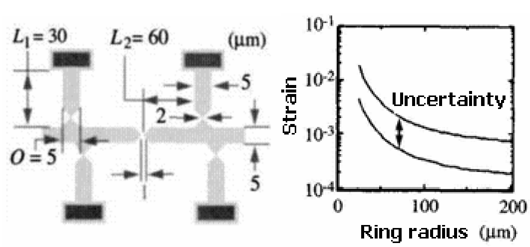

Fig. 3. Micro test structure at ring and beam for strain measurement (w = 5µm, R_0-R_i=20µm, R = 20-250µm) [8], [9].

For the rotation beam (Fig. 3), the strain-ε is calculated from the displacement of the tip Δy as [8], [9]:

$$\varepsilon = \frac{O\Delta y}{2L_1\left(L_2 + \frac{O}{2}\right)} \qquad (5)$$

This method can be applied both compression stresses and tensile stresses.

B. Young's Modulus

For microstructure the Young's modulus-E is determined by application of external force that lead of micro-deformation as microstructure shape, while for bulk material the value of E is define as a slop of strain-stress (ε-σ) curve, used (1) [2], [8], [9]. At thin film, the value of E is determined by an original MEMS method, presented in Fig. 4.

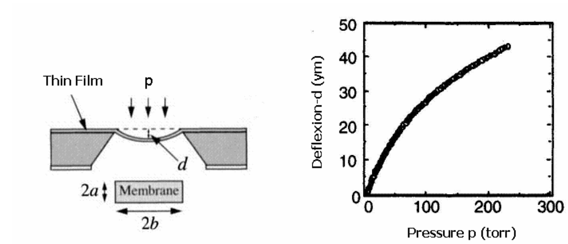

Fig. 4. Concept of the load-deflection measurement technique for simultaneous ε and E measurement [8], [9]

For testing, a thin film is deposit on a SCS substrate and that is anisotropic etching to form a thin film membrane. The deflection of thin film membrane center –d is measuring with changing pressure-p across the membrane, while its approximation to pressure-deflection behavior of membrane can be derived using an energy minimization method [8], [9]:

$$p = \frac{C_1(n)\sigma \cdot t \cdot d}{a^2} + \frac{C_2(n,\nu)E \cdot t \cdot d^3}{a^4} \qquad (6)$$

, where: t is the thickness of the thin film, a -the short side length of the membrane, n - the ratio between the short side of the membrane $2a$ and the long side of the membrane $2b$ $(n = a/b)$, ν- Poisson's ratio of the thin film, and $C_1(n)$ and $C_2(n, \nu)$ are dimensionless coefficients that depend on n and ν. Eq. (6) can be rewritten as [8], [9]:

$$\frac{p \cdot a^2}{t \cdot d} = C_1(n)\sigma + C_2(n,\nu)E\frac{d^2}{a^2} \qquad (7)$$

The value of E can be determined by strain-stress diagram, and C_1 and C_2 by analytically method.

C. Poisson's Ratio

General formula of strain-stress for anisotropic material is [2], [8], [9]:

$$\sigma_j = C_{jk} \cdot \varepsilon_k \,(j,k = 1,2,3...6) \tag{8}$$

, where: σ_j-is a stress vector, e_k - strain vector, and C_{jk} is a compliance matrix. By measuring E and ν, mechanical properties of thin films can be determined accurately. For in-plane strain fields, specific of isotropic materials, the ν is defined as [2], [8], [9]:

$$\nu = -\frac{\varepsilon_j}{\varepsilon_i} \tag{9}$$

Subscripts-i and j denote the direction parallel/ perpendicular to the applied stress).

For a majority metals the value of Poisson's ratio is in elastic range and has the value-0.3, which can rise to 0.5 in plastic deformation range as of constant keeping in material volume during plastic deformation process.

D. Yield Strength and Fracture Strength

The methods used for measuring of yield strength and fracture strength of MEMS materials are similar with that presented at Young modulus and Poisson's ration, required determination the stress-strain diagrams of tested materials, but in this case are need to resolve two significant problems, as [2], [8], [9], [11]:

- Stress applied materials for strength measurements imposes to be greater as for elastic tests,
- Accuracy of strength value must be higher that required defining of maximum stress in specimen that are directly influenced by the specimen boundary and specimen shape.

Also, a big problem represents at tensile testing of MEMS materials that is got by the fragility and small size of specimen which required carefully handling and immobilization on the chuck of a tensile tester. Tensile test consists in determination of strength stress-σ_s applied by a force-F along the displacement axis and S-cross-sectional area of the specimen [7]-[9], [11]:

$$\sigma_S = \frac{F}{S} \tag{10}$$

For brittle materials as single-crystal-silicon, poly-Si and dielectric films, which haven't elastic limits, the yield strength- σ_y is almost equal with fracture stress- σ_f.

A widely method used for testing of microstructure is AFM (Atom Force Microscopy) or XRF technique (X-ray Fluorescence) that allow the measuring of the elastic deformation of sample for thin film by a tensile intender with XRD (X-ray diffraction) from Fig. 5:

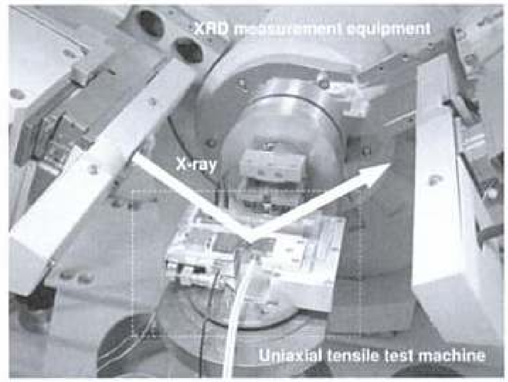

Fig. 5. Installation used for tensile test with XRD measurement equipment [8], [9]

E. Thermal Conductivity and Specific Heat

Thermal properties of MEMS materials suppose to determine the thermal conductivity-κ and specific heat-c. It's well known that for MEMS structures the thermal influence is important, such as their small dimensions that imposed thermal design carefully. So, more MEMS use temperature change as a sensing principle or actuation principle.

Widely method used at determining of thermal conductivity is the measurement of temperature change caused by known applied heat as in Fig. 6 [8], [9].

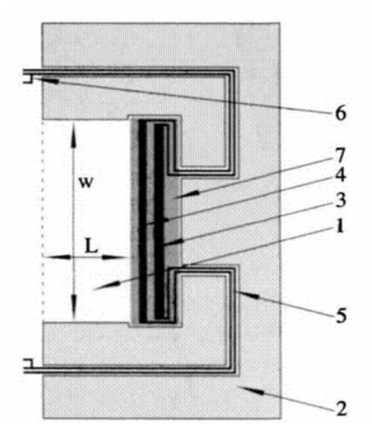

Fig. 6. Usually device structures to measure-κ [8], [9]

1- Cantilever, **2-** windows to etch single-crystal silicon under the cantilever, **3-** poly-Si heater; **4-** poly-Si temperature sensor; **5-** metal connection to pads; **6-** bifurcations into current and voltage lines for four point measurements; **7-** metal cover for temperature homogenization.

At this measurement device the heater and temperature sensors are electrically connected from thin suspension arms that allow that by applying of an electric current through heater to produce a heating as Joule's effect, which due to its circulation from console (thin film) to substrate. This flow heat results into a temperature change along the cantilever that permits to determine the thermal conductivity-κ as the amount of heat applied, the temperature change at free end and cross-sectional area of cantilever. This cantilever can be used like a reference to measure of thermal conductivity for any thin films deposited on it. In this case, if the temperature is measured at two temperature difference and the two temperature sensors are used to determine the thermal conductivity-κ.

At determination of heat capacity-c can be used a dynamic thermal response, which used an installation presented in Fig.7 that allows to measure both thermal parameters as heat capacity and thermal conductivity.

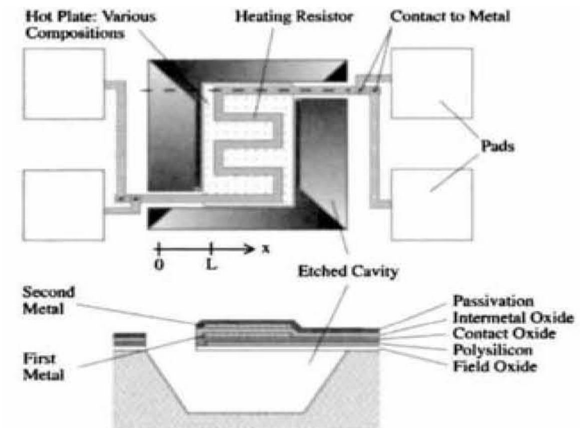

Fig. 7. Installation used at determination-c [8], [9].

The thermal conductivity of material is determining the static relationship between applied heat and change temperature of membrane. A poly-Si heater in spiral form is applied on the membrane, on which is applied a DC current-I_{AC} with angular frequency-ω due to change of constant DC term and dynamic temperature change. The amplitude-$A(\omega)$ and phase-φ is determine from thermal modeling and analysis of structure, and the voltage change of the poly-Si heater due to temperature change is written as [8], [9]:

$$A(\omega)\cos(3\omega t-\varphi(\omega)) \tag{11}$$

$$A(\omega)=\frac{U_0}{\sqrt{1+(\tau\omega)^2}} \tag{12}$$

$$U_0=\frac{R_o^2 L\beta}{4(2K+K_{rad})}I_{AC}^3 \tag{13}$$

$$\varphi(\omega)=arctg(\tau\omega) \tag{14}$$

$$\tau=\frac{2CL}{2K+K_{rad}} \tag{15}$$

Where: L-is the length of arm, K-thermal conductance of the supporting arm, K_{rad}-thermal loss due to radiation, Ro-resistance of poly-Si at room temperature, and β-is the temperature coefficient of resistance.

By using these relationships can be determine the κ and c parameters, while in final, a pair of structures with heat capacities-c_1 and c_2 led to plate composition differing by a single thin film of volume-V_{layer}, which is used to determine the volumetric-c_{layer} of this thin film [8], [9]:

$$c_{start}=\frac{c_2-c_1}{V_{strat}} \tag{16}$$

Can be observed from all measurements techniques used for determination of mechanical and thermal characteristics of MEMS samples required certain approaches which are specific of any material type and manufacturing process to obtain a desired microstructure.

III. Conclusion

This paper has presented some methods used for characterization and testing of materials used for MEMS. These methods used are differently as other materials because of their fragility, easy damages or fractures and small size of specimen at handling and testing, which needs special technique and installations adapted these conditions.

The accuracy of measurements required determination of high precision of results that are affected by the specimen boundary or specimen shape.

References

[1] R. Aronson, “Micromanufacturing: The new frontier”, *Manufacturing Engineering Magazine*, SME Editor, Vol. 138, No.5, May 2007, pp.89-100, Dearborn, MI, USA, 2007.
[2] B. Bhushan,, *Springer handbook of nanotechnology*, ISBN 3-540-01218-4, Springer-Verlag Berlin Heidelberg New York, 2004, pp. 85-260.
[3] O. Brand, G.K, Fedder, J.G., Korvink, C, Hirold, O. Tabata, *”Reliability of MEMS: testing of material and devices*”, WILEY-VCH Verlang GmbH & Co KGa Weinheim, Germany,2008, pp.45-250.
[4] S.A. Brown, “How own mechatronics? Mechanical, electrical, control, and software engineers all play a vital role in building electromechanical systems”, “*Mechanical Engineering”* ASME Magazine, Vol.130/No.6, June 2008, pp.24-29, New York, 2008.
[5] J.M., Jackson, “Microfabrication and nanomanufacturing”, CRC Taylor & Francis Editor, 2006, pp.45-125.
[6] S.T. Chiriacescu, I. Balcu, *Introduction in elasticity theory and mechanical resistance (English translation), Introducere în teoria elasticităţii şi rezistenţa materialelor”,* Editura Universităţii “Transilvania” din Brasov, ISBN 978-973-598-244-4, 2008, pp.25-130.
[7] I. Curtu, I., D.Luca-Motoc, *“Micromecanica Materialelor Compozite:Modele Teoretice”,* Editura Univ.“Transilvania” din Brasov, ISBN 978-973-598-469-4, 2009, pp. 25-160.
[8] P.J.G. Korvink, *MEMS: A practical guide to design, analysis, and applications,* William Andrew Publish, Springer, 2006, pp.55-145.
[9] P.A. Pop, *”MEMS- Introductive elements”,* University of Oradea Ed., ISBN 978-606-10-0249-8, Oradea, 2010, pp.53-111.
[10] P.A. Pop, G. Bejinaru-Mihoc,:2009, “MEMS an alternative for the future”, *Annals of the Oradea University, Fascicle of Management and Technological Engineering*, Vol. VIII (XVIII), pp.1332 -1339, Editor Univ. of Oradea, ISSN 1583-0691, 2009.