In-situ MEMS Testing

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ABSTRACT

Related to the dramatically smaller volume of microelectromecanical systems (MEMS), new methods in testing and qualification are needed. On single crystal silicon (SCSi) based devices, stress and loading in operation introduces defects during the MEMS life time and increases the risk of failure. Reliability studies on potential failure sources have an impact on MEMS design and are essential to assure the long term functioning of the device.

In this paper, mechanical tests such as tensile tests on SiSC beams are discussed to assess the resistance of SCSi structures upon loading. Defects introduced by DRIE, thermal annealing, dicing and bonding influence the crystalline perfection and have a direct impact on the mechanical properties of MEMS and on their aging behavior. Strain, defects and deformations are analyzed using High Resolution X-ray Diffraction Methods (HRXRD). Supporting simulations are done by Finite Element Method (FEM).

Keywords: reliability, microsystems, sensors, testing, x-ray diffraction.

1 INTRODUCTION

Microelectromechanical systems engineering involves complex design, manufacturing and packaging processes. MEMS such as sensors, actuators, electronic devices find applications in areas where a high reliability is needed, e.g. aerospace, automotive or watch industry. In consequence there is a strong demand in quality control and failure analysis [1-5]. Microsystems technology (MST) can be highly reliable, but differs from the reliability of solid-state electronics. Therefore testing techniques must be developed to accelerate MST-specific failures.

Single crystal materials, especially single crystal silicon is preferentially used in MEMS technology as it presents a high potential resistance against aging. The crystal quality is influenced by the steps of the entire engineering process. DRIE, thermal annealing, dicing and bonding influence the crystalline perfection and could favor failure.

For the understanding of failure it is essential to obtain further going information about the stressed material on the atomic scale. Therefore, detailed investigations have to be conducted, which includes the comparison of experimental methods as well as numerical simulations. Experimental measurements of local strain, deformations and the analysis of defects are approached by High Resolution X-ray Diffraction Methods.

In-situ mechanical testing (Fig. 1 and 2) on the HRXRD diffractometer is performed which allows to evaluate the strain, defects and deformation during the application of mechanical forces. The tensile tests are executed on SiSC beams (50 x 50 μm) fabricated by DRIE etching and different post treatments (Fig. 3). HRXRD (Fig. 2) with Rocking Curves (RC's) and Reciprocal Space Maps (RSM) is used as an accurate, non-destructive experimental method to evaluate the SiSC quality in MEMS, and more precisely for the given example, the *in-situ* strain, defects and also geometrical parameters such as tilt and bending of device parts. Simulations of deformations by FEM are carried out simultaneously using nonlinear constitutive laws based on well tested empirical molecular potentials existing for SCSi [9-11].

2 EXPERIMENTAL

A new testing setup was developed to perform mechanical testing on bending and on tensile specimen. The flat design of the apparatus allows *in-situ* mechanical testing on the HRXRD instrument which is performed and gives the possibility to evaluate the strain, defects and deformation during the application of mechanical forces

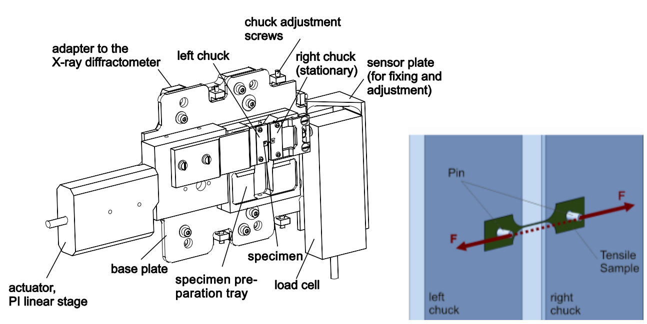

Fig 1: Experimental apparatus for tensile tests.

Fig. 2: HRXRD diffractometer with the mechanical test equipment.

The apparatus basically provides two rigid chucks – each with a press-fitted pin on the top –the right, stationary chuck is connected to a load cell and the left, actuated chuck is connected to a PI linear stage. As the two chucks and especially the two pins must be accurately parallel, several chuck adjustment screws allow the fine tuning of the load cell position as well as the orientation and the placement of the left chuck with respect to the right. Furthermore, the placement of the chucks may be controlled under an optical microscope as well as the dimension and alignment of the specimen.

The two pins allow a mechanically proper application of force on the sample in the sense of well-defined boundaries (no clamping, no glue). Furthermore, the modular setup allows the performance of experiments in horizontal and vertical direction respectively.

The tensile tests are done on SiSC samples with a diminution at the center part to a critical beam size of (50 x 50 µm). The tensile samples were fabricated using standard MEMS manufacturing techniques as photolithography and ICP/DRIE etching processes. Before placing and aligning the sample on the chucks, the two support strips are cut away so that the entire load is applied to the microbeam specimen.

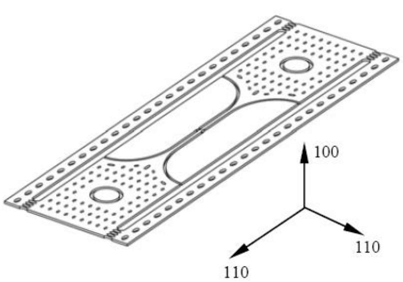

Fig. 3: SCSi sample used in the tensile test.

HRXRD with Rocking Curves (RC's) and Reciprocal Space Maps (RSM's, Fig. 4a and 5a) is used as an accurate, non-destructive experimental method to evaluate the SiSC quality in MEMS, and more precise for the given example, the *in-situ* strain, the defects and also the geometrical parameters such as tilting and bending of the device parts.

3 RESULTS

After precisely determining the critical center part of the tensile loaded specimen by a sequence of Rocking Curve measurements along the beam, HRXRD (Fig. 4a) Reciprocal Space Maps (RSM's) were performed at that position on the (004) and (440) peaks (Fig 4a and 5a). With a x-ray beam width of 200µm, both the 50x50µm thin center and a small area broader part of the beam is measured in the RSM.

The corresponding FEM simulations of the loaded tensile sample are performed with a nonlinear hyperelastic constitutive law using the strain energy density derived from the Modified Embedded Atom Method (MEAM) potential [11] (Fig. 4b and 5b).

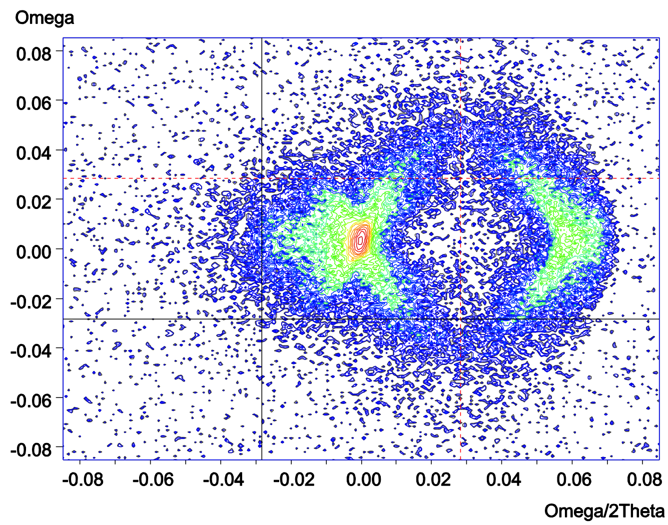

Fig. 4a : RSM on the (004) peak.

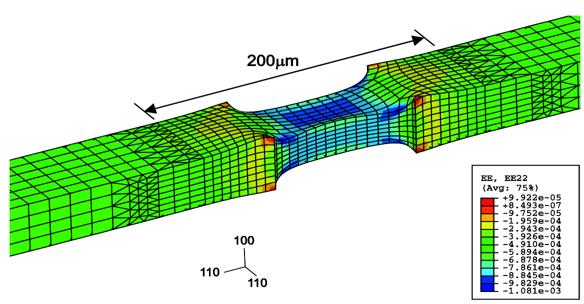

Fig. 4b: FEM simulation of the strain in [100]-direction

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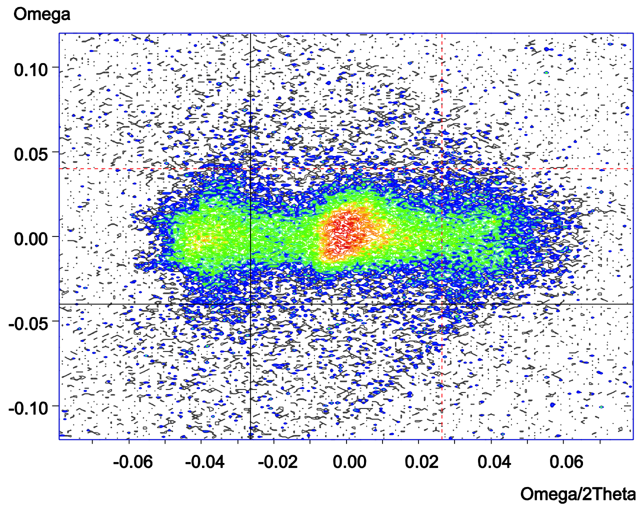

Fig. 5a : RSM on the (440) peak

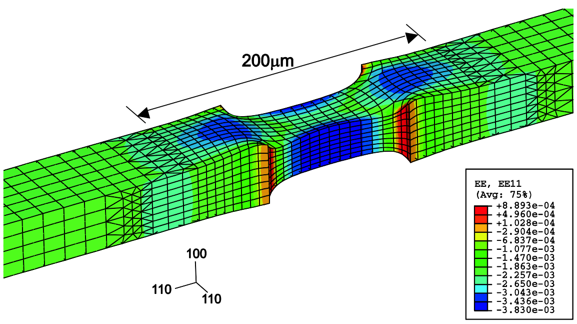

Fig. 5b: FEM simulation of the strain in [110]-direction.

4 DISCUSSION

MEMS devices can operate on a wide variety of physical principles for actuation, the most common being electrostatic, thermal, magnetic, and piezo-electric. The wide variety of materials and physical principles used make general statements about MEMS reliability difficult. However the discussed x-ray techniques permit to get access to the amount of defects in any case without sample preparation. HRXRD is a non-destructive quality control tool permitting to follow up the entire MEMS production process like the DRIE processing, post treatments such as thermal annealing, and MEMS packaging. The application of different techniques such as reciprocal space mapping, rocking curve and omega / 2theta scans have been shown to monitor the stress state of a structured SiSC device.

It has been shown, that applied stresses and also defects can be monitored. Important information can be revealed from RSMs separating lattice strain and tilt out of different diffraction planes.

Concerning the SCSi structured samples the HRXRD results show that upon tensile strain, defects will occur and influence the reliability and the aging of such devices [6-8]. Especially for medical devices and for space applications it is of great importance to be able defining the mechanical limits of the processed parts and to determine the mobility of defects which are the “precursors” of the aging.

Fig. 4a and 5a show the RSM’s made on two different SCSi beam orientations. The Bragg peak at lower omega/2theta ($\omega/2\theta \sim 0$) values corresponds to the thicker and therefore less strained part of the tensile sample (Figure 4a) while the broader and less intense maximum at higher omega/2theta values corresponds to the thinnest and most strained part (Figure 4a).

The RSMs may be analyzed with Bragg’s law (1) and its differentiation (2). With the knowledge of the position of the Bragg peak, the value of θ and $\omega/2\theta$ respectively, the spacing d between the planes in the atomic lattice may be calculated by the known wavelength of the x-rays. The differential form describes the relationship between the shift of the Bragg peak $\Delta\theta$ and the change of the lattice spacing Δd due to a present state of stress.

$$n\lambda = 2d_{hkl}\sin\theta_{hkl} \tag{1}$$

$$\Delta\theta = \frac{\Delta d}{d}\tan\theta = -\varepsilon\tan\theta \tag{2}$$

The strain ε can directly be revealed from $\varepsilon=\Delta d/d$ and stresses are calculated using the linear elastic case by $\sigma=\varepsilon\cdot E$ (E=Young’s modulus).

In this context the difference of strain $\Delta\varepsilon_{RSM}$ between the two Bragg peaks (fig. 4a) of the thinner and broader part of the specimen is calculated with respect to the particular position of the maximal intensity. The corresponding FEM calculations, $\Delta\varepsilon_{FEM}$ between the more or less homogeneous strain values on the border of the broader part and the maximum strain value in the center part, agree well with the experimental results. Regarding the 200µm wide illuminated area of the sample (fig. 4b), the values for $\Delta\varepsilon_{FEM}$ and $\Delta\varepsilon_{RSM}$ have a divergence of 0.01-5%. Similar results for the divergence of the calculated strain are obtained for the measured RSM on the (440) peak and corresponding FEM in [110] direction (fig 5a and 5b).

In addition to the direct access of the crystal lattice strain, also a lattice tilt is observed from RSM measurements. The drift in omega with respect to omega=0 indicates the absolute lattice tilts in the regions of dramatic strain changes being well presented in the FEM figures (Figures 4a, 5a). Furthermore the visualization of the complex state of deformation of the beam by FEM makes the shapes of the RSM understandable and explainable. As the sample is symmetrical, these geometrical features are represented symmetrically in +/- omega.

The combination of mechanical testing, HRXRD and FEM show a valid approach to discuss materials robustness but also the aging behavior through accelerated testing in MEMS applications.

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REFERENCES

[1] A. Dommann, A. Neels, The role of strain in new semiconductor devices, Advanced Engineering Materials, 11, 275-277, 2009.

[2] A. Neels, A. Dommann, A. Schifferle, O. Papes, E. Mazza, Reliability and Failure in Single Crystal Silicon MEMS Devices, Microelectronics Reliability, 48, 1245-1247, 2008.

[3] A. Neels, P. Niedermann, A. Dommann, Life time predictions through X-ray defect analysis of MEMS devices, Materials Science Forum, 584-586, 518-522, 2008.

[4] E. Mazza, J. Dual, Mechanical behaviour of a mm-sized single crystal silicon structure with sharp notches, J. Mechanics and Physics of Solids 47 (1999), 1795-1821

[5] J.J. Wortmann and R.A. Evans, Young's modulus, shear modulus and Poisson's ratio in silicon an germanium, J. Appl. Phys., Vol. 44, 534-535, 1973

[6] Arney S.; *Designing for MEMS Reliability*, MRS Bulletin, April 2001, p. 296

[7] Herbert R. Shea ; *Reliability of MEMS for space applications*, Proc. SPIE Int. Soc. Opt. Eng. 6111, 61110A (2006)

[8] Dommann A., Enzler A., Onda N.; *Advanced x-ray analysis Techniques to Investigate Aging of Micromachined Silicon Actuators for space Application*, Microelectronics Reliability, 43 (2003) 1099-1103

[9] F.H. Stillinger and T.A. Weber, *Computer simulation of local order in condensed phase of silicon*, Physical Riview B, 31(8):5262-5271, April 1985

[10] M.I. Baskes, *Application of the Embedded-Atom Method to Covalent Materials: A Semiempirical Potential for Silicon*, Physical Review Letters, 59(23):2666-2669, December 1987

[11] M.I. Baskes, *Modified embedded-atom potentials for cubic materials and impurities*, Physical Review B, 46(5):2727-2742, August 1942