Advanced In- and Out-off plane High Resolution X-ray Strain Analysis on MEMS

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ABSTRACT

Related to the dramatically smaller volume of microelectromecanical systems (MEMS), new methods in testing and qualification are needed. In 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, the applications of advanced High Resolution X-ray Diffraction (HRXRD) methods in strain, defect and deformation analysis on MEMS are discussed. Stresses and defects changes in the devices during the fabrication process (DRIE, annealing, bonding) influence the MEMS silicon quality and therefore have a direct impact on the mechanical properties. The applied in-plane diffraction technique allows to obtain additional information about the device stress state being not accessible by symmetrical out-off plane HRXRD methods.

Keywords: reliability, microsystems, strain analysis, testing, x-ray diffraction.

1 INTRODUCTION

The engineering of Microelectromechanical systems (MEMS) involves complex design, manufacturing and packaging processes. MEMS find applications in areas where a high reliability is needed such as in aerospace, automotive or watch industry. This creates a strong demand in quality control and failure analysis [1-3] and also brings new challenges, particularly in the fields of testing and qualification.

Single crystal materials, especially single crystal silicon (SCSi) presents a high potential resistance against aging. The crystal quality is influenced by the steps of the entire engineering process involving manufacturing and packaging and requires therefore specific design rules. DRIE, thermal annealing, dicing and bonding influence the silicon crystal structure and will increase the probability of failure. For its understanding it is essential to obtain further going information about the stressed material on the atomic scale. Detailed investigations have to be therefore 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 carried out by High Resolution X-ray Diffraction Methods (HRXRD).

2 EXPERIMENTAL

Micro-grids have been structured into 4 µm thick silicon single crystal layer which was previously anodically bonded onto a pyrex substrate (Figure 1). Stresses depend on the bonding process parameters such as voltage and temperature and also on the structuring procedure. The grids are actuated and their functioning is correlated to the stress state in the silicon layer.

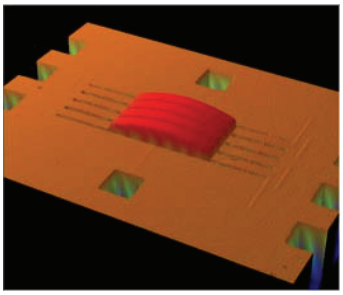

Figure 1: MEMS part showing the SiSC layer with the released and bended grid.

The stress introduced into the MEMS by the applied anodic bonding process can be determined by non-destructive High Resolution X-ray Diffraction (HRXRD) methods. For the HRXRD measurements, a PANalytical X'Pert PRO MRD instrument equipped with a Göbel mirror and a Bartels-4-crystal monochromator at the incident beam side and a xenon point detector at the diffracted beam side has been used. Measurements were carried out using copper $K_{\alpha 1}$ radiation. The quality of the silicon single crystal lattice was analyzed by means of X-ray Rocking Curves (RC's, details given in Figure 2, detector 2) and Reciprocal Space Maps (RSM's, Figure 2, detector 1) which is used as accurate, non-destructive experimental method to evaluate the SiSC quality in the MEMS device.

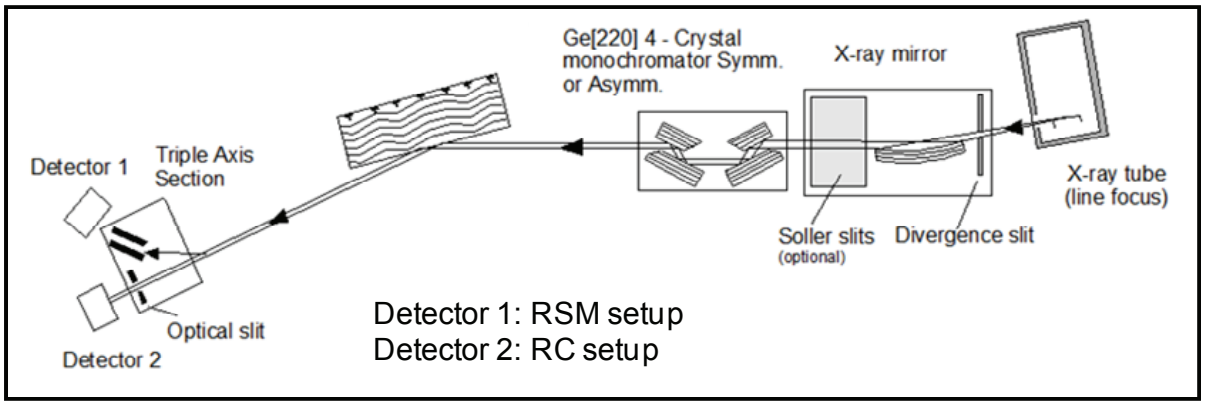

Figure 2: High resolution diffractometer setup for investigations on SiSC based MEMS and semi-conductor materials. Detector 1: RSM measurements and Detector 2: RC measurements.

For the micro-grids being discussed here the strain state, defects and also geometrical parameters can be derived.

The application of RSM's to the system under investigation allows the separation of strain and geometrical features being present in the SiSC device (Figure 3a). For an epitaxially grown thin film, two distinct peaks are observed (RSM and RC) which is related to the different lattice parameters of substrate and layer material (Figure 3c). In the structure, a strain gradient in the SiSC is observed corresponding to a gradually change in lattice parameters. In the RSM and RC, an asymmetric peak broadening is observed.

In rocking curves, the strain component superposes with lattice tilts eventually present. In MEMS, where complex structural features may be present, bending and tilts of parts are often observed. An efficient separation of strain and lattice tilt is only possible by carrying out reciprocal space maps (Figure 3a). Related to modern HRXRD techniques these 2D scans are carried out time efficiently. The enormous gain in information from RSM versus RC measurements is obvious.

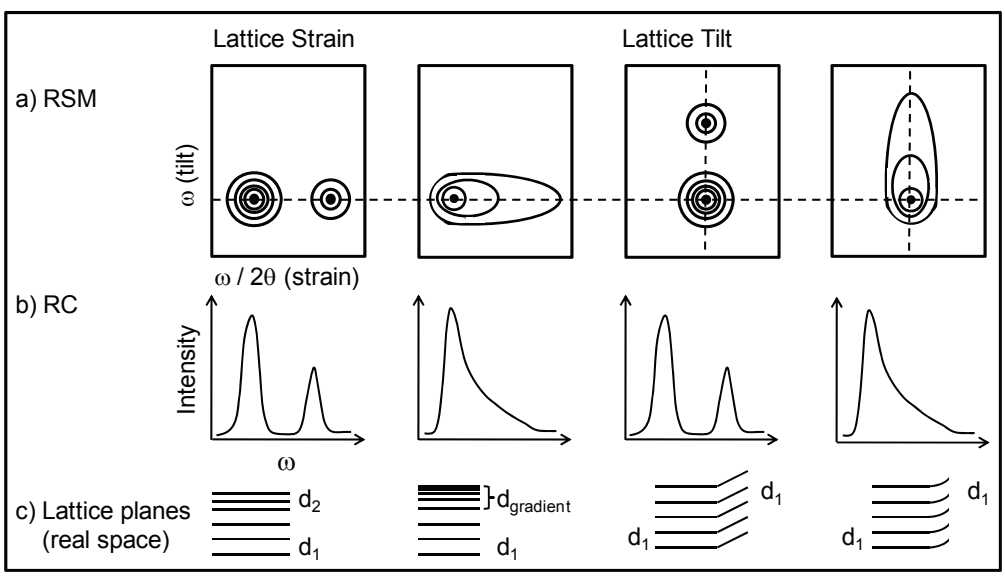

Figure 3: Schematic representation of HRXRD methods used for MEMS characterization: a) RSM on a symmetrical reflection such as (004) for SiSC (001) devices; b) RC on the same sample and c) representation of the corresponding real crystal.

Out-off plane diffraction on the sample surface gives direct information about axial stresses being perpendicular to the surface. In addition to this conventional X-ray diffraction, also in-plane diffraction is applied. In-plane diffraction offers direct access to the strain parameters being parallel to the sample surface.

3 RESULTS

Figure 4 shows the RC and RSM (out-off plane) measured on the micro-grids. The RC shows the Si(004) Bragg peak with a small asymmetric peak broadening to larger lattice parameters corresponding to a small tensile strain in the layer. The very high plateaux-like intensity over a large omega area indicates the tilt of the grids. While a superposition of both is observed in the omega scan (Figure 4a), the RSM allows the separation of strain and tilt features (Figure 4b). The bending of the released SiSC structure can be determined with a maximum of 0.4° (symmetrical to the left and right side of the sample).

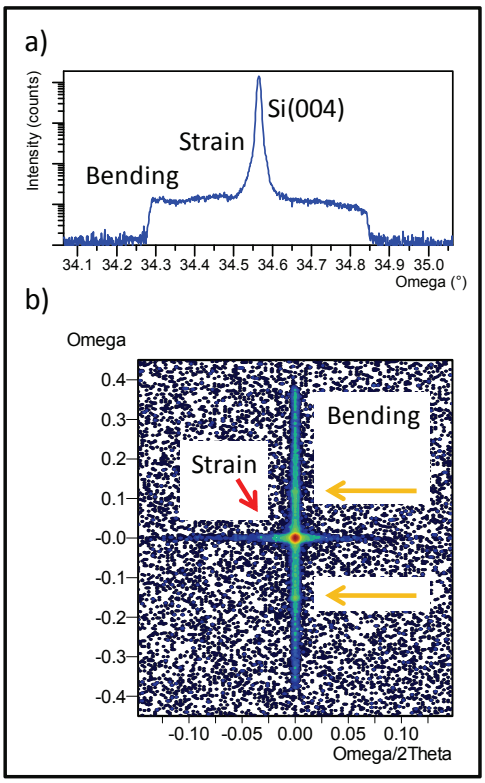

Figure 4: HRXRD on the structured part of the chip a) RC and b) RSM.

The accurate determination of the 2Theta value (Figure 5) being related by Bragg's law to the d-spacing results in a nearly perfect agreement to the reference SiSC. The strain gradient to higher lattice parameters perpendicular to the SiSC layer (lower lattice parameter in-plane) shows that the bonding process results in a small compressive in-plane stress close to the bonding side. Complete relaxation occurs going from the bonding interface to the surface.

The signal of the relaxed and bended Si-beams coincident with the Si(004) peak position from the relaxed part of the 4µm thick SiSC layer (Bragg main peak).

As a consequence, measurements on a part on the chip where no structure is present results in the same strain gradient but not recording the lattice tilt features in the recorded RSM (Figure 5b). Peak profile fitting of the omega/2theta scan reveals the out-off plane strain leading to a stress value of +120(5) MPa. The according in-plane Si layer stress close to the glass interface is determined with -35(5) MPa. This compressive in-plane strain is therefore responsible for the bending of the Si-beams.

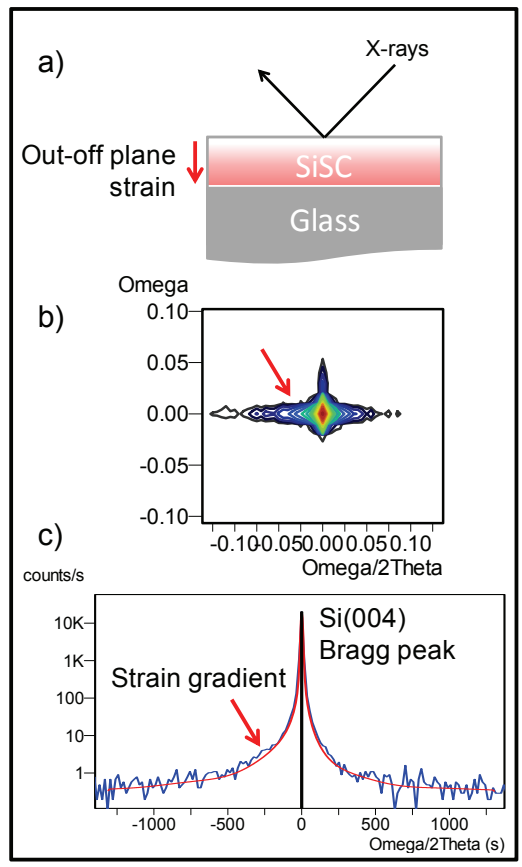

Figure 5: Out-off plane diffraction: a) scheme; b) RSM; c) ω/2θ scan.

Going from out-off plane measurements carried out on the symmetrical Si(004) reflection on the sample surface (device layer) to in-plane measurements on the symmetrical Si(440) reflection on the 4µm thick sample side surface, permits the direct access of in-plane stresses from crystallographic planes being perpendicular to the sample surface.

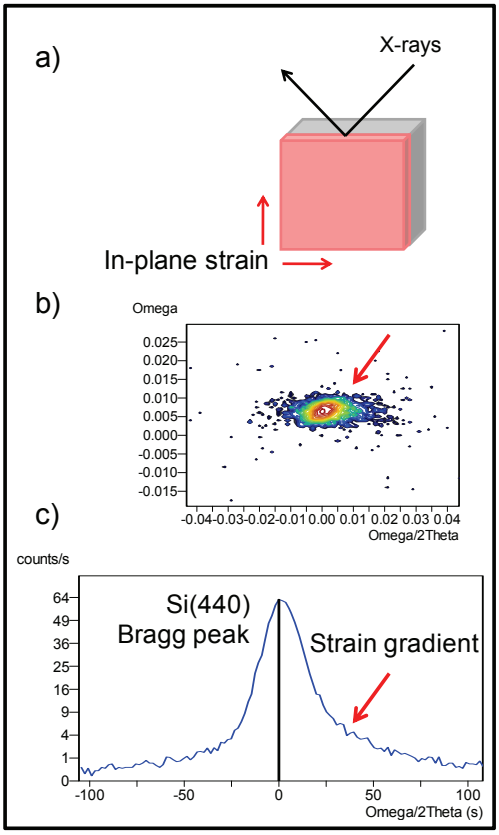

Figure 6: In-plane diffraction: a) scheme; b) RSM; c) ω/2θ scan.

The in-plane diffraction technique delivers important strain information about the undesired bending of the SiSC grids. Figure 6a shows the X-ray beam path on the sample. Recording the RSM (Figure 6b) and the omega / 2theta (Figure 6c) measurements on the small 4µm large area results in low X-ray intensities of the diffracted beam. Nevertheless, the train gradient can be revealed. An asymmetry on the right side of the Si(440) Bragg peak indicates compressive strain for the in-plane strain of the sample device layer. According to Poisson, in a fully strained sample the in-plane stress is much smaller compared to the axial stress. The asymmetry related to compressive in-plane stress is less pronounced than for the out-of plane tensile stress.

4 DISCUSSION

In MEMS fabrication, a close survey of the strain state of the used materials and the entire device during its processing becomes important. The final device performance and also its reliability will depend on these parameters. HRXRD is a non-destructive quality control tool permitting to follow up the entire MEMS production process. 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 layer anodically bonded to glass. It has been shown, that bonding stresses can be monitored.

Concerning the SiSC micro-grids structured into a thin SiSC layer bonded to glass, the HRXRD results show that even under small compressive strain, a bending of the released beams occurs. The aim would be to avoid the bending of the released SiSC structures. This could be done by changing the parameters of the applied bonding process. Small tensile stresses within the 4µm thick SiSC layer will result in no bending and a good device performance.

Important information about the strain state of a device layer can be revealed from RSMs on the device layer. The application of in-plane diffraction methods delivers the in-plane layer stress in a direct manner. The knowledge of the strain tensor helps in understanding to identify potential failure and aging mechanisms. Therefore, HRXRD can support an improved device design which than leads to an adapted fabrication process.

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