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Mechanically probing time-dependent mechanics in metallic MEMS

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ABSTRACT

The reliability of metallic micro-electromechanical systems (MEMS) depends on time-dependent deformation such as creep. To this end, a purely mechanical experimental methodology for studying the time-dependent deformation of free-standing microbeams has been developed. It is found most suitable for the investigation of creep due to the simplicity of sample handling and preparation and setup design, whilst maximizing long term stability and displacement resolution. The methodology entails the application of a constant deflection to a μm -sized free-standing aluminum cantilever beam for a prolonged period of time. After this load is removed, the deformation evolution is immediately recorded by acquiring surface height profiles through confocal optical profilometry. Image correlation and an algorithm based on elastic beam theory are applied to the full-field beam profiles to yield the tip deflection as a function of time. The methodology yields the tip deflection as function of time with ~ 3 nm precision.

1. RELIABILITY AND TIME-DEPENDENT MECHANICS

The application of metals as structural components in MEMS is common for 'radio-frequency MEMS' (RF-MEMS). Figure 1 shows an example. The reliability of these devices has been shown to critically depend on time-dependent mechanics, such as fatigue and creep [1]. Fatigue affects the device life time through its limitation on the number of device operation cycles, e.g. the number of open/closed cycles of an RF-MEMS switch. Creep can directly affect the operational characteristic, e.g. through a shift in pull-in voltage of an RF-MEMS switch which results in a reduced power handling [2]. Whereas fatigue effects may pose less of a problem than expected at small geometrical length scales [3], the detrimental influence of creep seems to increase upon miniaturization [3].

Figure 1: Scanning electron micrograph of an RF-MEMS switch (courtesy of EPCOS Netherlands B.V.).

The difference between micro- and macroscale creep is generally attributed to the size-effect: the interaction between microstructural length scales and dimensional length scales [4,5]. The physical micro-mechanisms of creep in these free-standing microbeams are, however, poorly understood, let alone implemented in models. In the literature some reports can be found discussing creep and relaxation effects in thin aluminum films [6-11].

However, specifically for free-standing thin films not much research has focused on determining size-effects in time-dependent material behavior [12]. Therefore, there is a clear need for detailed studies into the physical micro-mechanisms underlying the size-effects in creep in metallic MEMS.

As a first step towards such studies, the goal of the current work is to construct and validate an experimental mechanical methodology to quantify creep, of μm -sized free-standing cantilever beams. To this end, first the factors are discussed that determine the choices for the design of the experiment, followed by the explanation of the methodology. Next, proof-of-principle measurements are conducted and the results are presented. Finally, conclusions are drawn with respect to the goal of this work and the further application of this work to the study of size-effects in creep in metallic-MEMS.

2. DESIGN OF EXPERIMENT

Performing mechanical tests on specimens that are free-standing and have dimensions in the order of a few micrometers or less is not trivial. Aspects of sample preparation, handling, loading, load and deformation measurement and control have to be carefully addressed [13]. Considering the sample preparation and handling, it is highly preferred to test free-standing, micron-scale on-wafer samples that have been fabricated in the same micro-fabrication process as that of the actual MEMS device. This simplifies the handling of μm sized samples to handling $20 \times 20 \text{ mm}^2$ dies/wafer pieces. It also guarantees that the results obtained in an experiment are fully applicable to the corresponding MEMS device. A small and simple displacement controlling mechanism is most suited to yield long term stability of the load and displacement control and measurement: this is especially critical for prolonged creep measurements. Therefore, a so-called ‘micro-clamp’ is designed, which is a simple horizontal knife-edge attached to an elastic hinge, see Figure 2. A differential screw is used to control the height of the edge with respect to the substrate to $\sim 50 \text{ nm}$, whilst simple adjustment screws are used for in-plane adjustment with $\sim 5 \mu\text{m}$ accuracy. The compact and near-monolithic fully mechanical design minimizes drift due to temperature and electrical effects. With optical confocal profilometry the out-of-plane deformation is measured, yielding full-field deformation information, with 10-nm RMS repeatability (on an ultra-flat surface) for the high magnification super long working distance objective used here. Interferometric profilometry is not suitable as a large working distance ($>5 \text{ mm}$) is imposed by the micro-clamp and large local surface angles are associated with the relatively high surface roughness of the investigated metallic MEMS surface. The measurement precision will benefit from the full-field deformation imaging combined with simple image processing and analysis with elastic beam-bending theory. Another advantage of this methodology is that multiple samples can be deflected in parallel simply by aligning all samples on the chip and using a broad knife-edge. Furthermore the setup does not involve any highly specialized parts or instruments which allows for easy and inexpensive parallelization. This is particularly useful for prolonged creep experiments. The only drawback is the lack of a direct measurement of force. Given the benefits of this methodology, i.e. simplicity, long term stability, deflection resolution, it is found most suitable.

Figure 2: (Left) Schematic of the MEMS cantilever deflection experiment with a micro-clamp under a confocal optical profilometer, which monitors the deflection as function of time. (Right) Schematic representation of the measurement sequence of the cantilever deflection recovery experiment: (A) the knife-edge of the micro-clamp approaches the cantilever; (B) the knife-edge deflects the cantilever to a depth of δ_{loading} and holds it there for a certain period of time; and (C) the edge is raised, releasing the cantilever, after which the deflection recovery is measured over time using a surface profilometer.

Based on these considerations, the choice has been made to design an experiment measuring the time-dependent deflection recovery of a cantilever after constant deflection. Figure 2 shows the deflection sequence. The initial deflection is controlled by the ‘micro-clamp’. Directly after release of the deflection, a time series of full-field deformation maps is acquired with a commercial confocal optical profilometer. An algorithm based on elastic beam theory is then applied to the deformation data to extract the evolution of the deflection as function of time. This methodology thus allows simple sample handling and MEMS-device fabrication, and precise control and measurement of the deformation over a longer period of time.

3. EXPERIMENTAL PROCEDURE

The deflection of the microbeam test structure is controlled by the micro-clamp. This is done under the optical profilometer, a Sensofar Plu2300. The surface profilometer is operated in the confocal microscopy mode: 470 nm LED light, 100x long working distance objective with N.A. of 0.7, height of scan of 20 μm , data acquisition time ~ 85 s. In this configuration, the RMS repeatability is <10 nm, although data acquisition and processing will improve the overall precision. Finally, the (optically flat) substrate is leveled to within 0.01° by using the interferometric mode of the optical profilometer and manually adjusting a 2-axis tilt stage. The setup is stabilized on an active vibration isolation table. The measurements are conducted in an environmentally controlled room, with $T_{\text{ambient}} = (21.0 \pm 1.0)^\circ\text{C}$, $RH = (14 \pm 1)\%$.

Figure 3 shows an example of the cantilever beam test structures investigated here. The microbeams are produced from Al-Cu (1 wt%) on a test-wafer having undergone a production process scheme as used for actual RF-MEMS switches. The Young's modulus is 66.8 GPa, determined by eigenfrequency measurements and finite element analysis of electro-statically actuated cantilevers [14,15]. The film thickness is $(4.8 \pm 0.2) \mu\text{m}$ and has a surface roughness $R_A = 45$ nm. The film consists of columnar, through-thickness grains with an average grain diameter of 20 μm (assuming cylindrical grain shapes) and a strong $\{111\}$ surface orientation, as determined with electron backscatter diffraction. Several beams having a width of 25 μm and lengths between 45 and 500 μm are located on the test-wafer. Cross-sections are trapezoidal due to the thin film patterning. For the current work, beams of 65 μm length are utilized. This choice is a trade-off between practical imaging, deflection and induced stress levels. The experiment is conducted as follows. The wafer is placed on the micro clamp and the beam is aligned to the knife-edge (with $\sim 5 \mu\text{m}$ lateral precision) under the microscope. Leveling (to within 0.01°) is conducted with interferometry. A surface topography of the unaltered beam (reference height position) is acquired in the confocal profilometer mode. The knife edge is then lowered to deflect the beam to a depth of approximately 800 nm (much less than the microbeam-substrate gap of 3 μm). This level is chosen as it corresponds to $\sigma_{\text{bend,max}} = 50$ MPa for this length. This stress level corresponds to $\sim 30\%$ of the yield stress of the material and is a lower level encountered in RF-MEMS device operation. The beam is then kept deflected at this position for 48 hours, after which the unloading procedure is started. The edge knife is raised and immediately thereafter, at every 85 s, surface topographies are obtained for a duration of 10000 s. Finally images are taken every 900 s for another 10000 s. In this manner a set of surface profiles is obtained of the recovering deformation in the beam.

Figure 3: (Left) A SEM-image of a test cantilever beam that is attached to a free-standing plate clamped on three sides by an anchor. (Right) A (mirrored) contour map of a profile of a beam placed under the micro-clamp obtained with confocal profilometry.

The surface profiles do not immediately yield the tip deflection as function of time. Data processing is required to deal with image translations and tilt due to thermal and various other drifts in the optical profilometry set-up. Therefore, an analysis procedure is implemented in Matlab to correlate x-y translations with pixel resolution and level with a linear fit. The tip deflection is determined by fitting standard beam bending theory to the full-field

deformation data of the beam. This uses the intrinsic assumptions that the bending profile is elastic and that the double clamped plate effectively fixes the beam. Area bins along the beam's length are created, in which the average height is determined to minimize height measurement error. These are the plot to form a profile, to which the equation for a single clamped beam is fit. Figure 4 shows this result.

Figure 4: Surface profile schematically illustrating the area bins and selected reference areas, all of which are schematically drawn here for clarification purpose. The mean height of these boxed areas is evaluated to form a profile. Linear plane fitting is applied based on the reference areas to correct for tilt around x and y axis. These areas are then used as reference height and set to zero height. The profiles are referenced to this height. Standard beam bending equations are fit to the profile as indicated by the dashed line in the lower graph. For clarification, a semi-circle is drawn at the location of the tip.

Figure 5: Results of the obtained profiles after deflection at ~800 nm for a duration of ~48 hours. Note that the surface roughness of the metallic MEMS is much higher than the change in tip deflection, which is of interest. The initial profile (acquired before any applied deflection) is plotted in black. The first profile acquired after unloading is plotted in blue and subsequent profiles are plotted with a gradient from blue to red. The dotted lines represent unreliable data, as the micro-clamp is partially blocking the reflection of light. Three sections are distinguished: (1) the micro-clamp, (2) the profile of the beam, and (3) the reference height region.

4. EXPERIMENTAL RESULTS

The result of the measured deflection recovery is a sequence of profiles, shown in Figure 5, from which the tip deflection as a function of time is determined, as shown in the left graph of Figure 6. After an instantaneous initial spring back of more than 95% of the loading depth, the beam shows a relatively small, though clear monotonous increase in height of ~20 nm over a time period of about 3 hours. This is evidence of time-dependent recovery of the cantilever. Next to this, a permanent deflection of ~10 nm is observed. To assess the precision of the measurement a fit is made to the tail of the graph where the deflection has saturated. A histogram based on the difference between average and measured deflection then shows that the tip deflection measurement has a precision (1σ) of ~3 nm, as shown in the right graph of Figure 6. This precision is quite substantial considering the ~45-nm RMS surface roughness and 10-nm RMS repeatability of the confocal profilometry (on a perfectly flat surface). The measurement has been repeated for several similar beams, all revealing similar results.

Figure 6: (Left) The displacement of the tip versus the logarithm of time. A fit (dashed line) is made for the time segment from 10.000-25.000 seconds. (Right) Histogram based on the data of the last 10000-25000 seconds to evaluate the precision of the measurement. From this a standard deviation in the tip deflection measurement of ~ 3 nm is estimated.

5. CONCLUSIONS

An experimental methodology is presented together with measurement results to measure time-dependent deformation in μm -sized free-standing aluminum-copper alloy cantilever beams. As a first result the deformation recovery of a microbeam is measured over a period of ~ 6 hours, showing a recovery of 20 nm during this period after initial spring back. A permanent deflection of ~ 10 nm is observed. The precision (1σ) is ~ 3 nm, which is quite substantial considering the relatively high surface roughness and unavoidable experimental limitations.

The measurement is possible due to the design of the experiment: measuring time-dependent recovery with confocal profilometry in a simple mechanical setup with minimal sample handling. A micro-clamp deflects on-chip micro-beams to a depth that can be controlled with ~ 50 nm precision (but can be measured again with ~ 3 nm precision). At the same time, the methodology is insensitive to thermal fluctuations.

The next step in this research is to apply time-dependent material models incorporated into FEA to extract physically meaningful parameters, the procedure of which will be published in the future. With this full methodology in place, grain size and grain orientation effects can be probed by coupling measured differences in grain size and grain orientation distributions between different microbeams of the same geometry (on the same wafer) to changes in the observed creep behavior. Furthermore, experiments can be conducted at various temperatures to accelerate or probe different creep mechanisms. Ultimately, device structural dimensions will be varied to probe more size-effects in creep of these structures.

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