Identification of Residual Stress State in an RF-MEMS Device

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INTRODUCTION

Microelectromechanical Systems (MEMS) are among the most significant technological advances of this decade. The objective of this technology is to manufacture "systems" whose dimensions are only a few hundred microns. Devices with applications ranging from drug delivery systems to telecommunications are currently under development. Their reduced size and weight give them unique advantages.

Most of our knowledge about materials behavior under elastic and plastic loading conditions fails to describe cases in which a characteristic dimension is of a few nanometers.

The study of "thin films" and "ultra thin films" employed in MEMS devices is being vigorously pursued. However, it is far from complete. Each MEMS device that is considered seems to exhibit differences in mechanical behavior and introduces new fundamental questions. This is a consequence of the strong effect that size introduces on fracture, plasticity, friction and fatigue.

In this investigation, Young's modulus and residual stress state of a freestanding thin membrane are characterized by means of wafer level tests. The membrane is part of an RF MEMS Switch manufactured by Raytheon Systems Co. The investigation uses a new method that combines nanoindentation, a Membrane Deflection Experiment (MDE) and 3D numerical simulations.

THE RAYTHEON'S RF MEMS SWITCH

The RF MEMS switch technology developed by Raytheon Systems Co. provides advantageous characteristics for communication circuits by virtue of its small size, low weight and low loss. Other applications of this technology are satellite communications, wireless Internet, radar, etc. The structure of one MEMS switch is shown in Figure 1. An aluminum membrane is electrostatically activated by an RF path. The membrane has a bow-tie shape and is supported at the ends by metal posts.

It is known that the mechanical properties of the aluminum membrane strongly determine the performance of the device. Particularly, it is of interest to experimentally measure Young's modulus (E), hardness (H), residual stress and failure modes of the membrane.

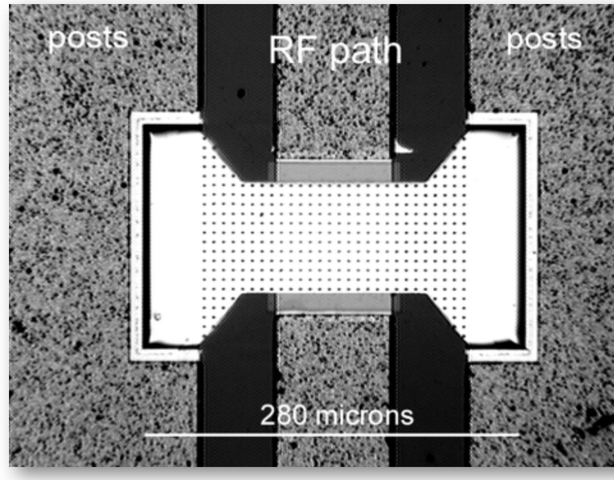

Figure 1: Top view of MEMS switch.

EXPERIMENTAL/COMPUTATIONAL APPROACH

A complete review of the literature was carried out to find out which experiments could be suitable for this special problem. In view that no specially designed samples were possible, a novel hybrid wafer level technique is proposed to address this investigation. The experimental-computational approach consists in performing:

- Nanoindentation tests: to provide an estimate of the mechanical properties of the membrane, including hardness and Young's modulus, independently of the structural behavior. Figure 2 shows a typical indentation mark and the Young's modulus as function of indentation depth.

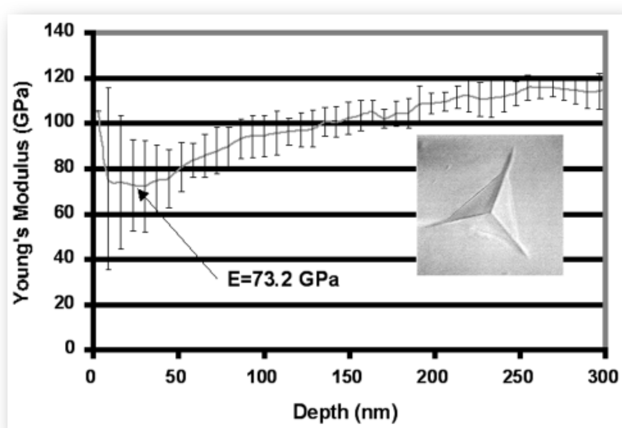

Figure 2: Nanoindentation results.

▸ Membrane Deflection Experiments (MDEs): to analyze the residual stress state of the membranes. Residual stresses (σ_0) are always present in thin films due to the microfabrication processes. Pushing the membrane down tests the specimen's structural response (see Figure 3). A Nano Indenter® XP system with a wedge tip is used to apply a line load.

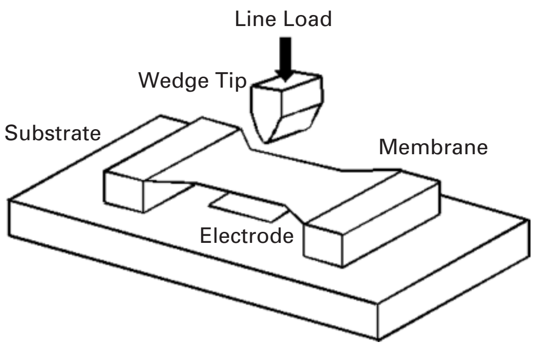

Figure 3: Schematic of the MDE.

▸ Finite Element Analysis (FEA): to match the experimentally measured load-deflection curve. In these analyses, residual stress (initial conditions) and Young's modulus are varied. The elastic constants estimated from nanoindentation are used in the analyses in which the residual stress is varied. The initial shape of the membrane is obtained by means of Atomic Force Microscopy (AFM). The analysis was conducted using ABAQUS Implicit. Different membrane and tips have been used to identify E and σ_0. See Figure 4.

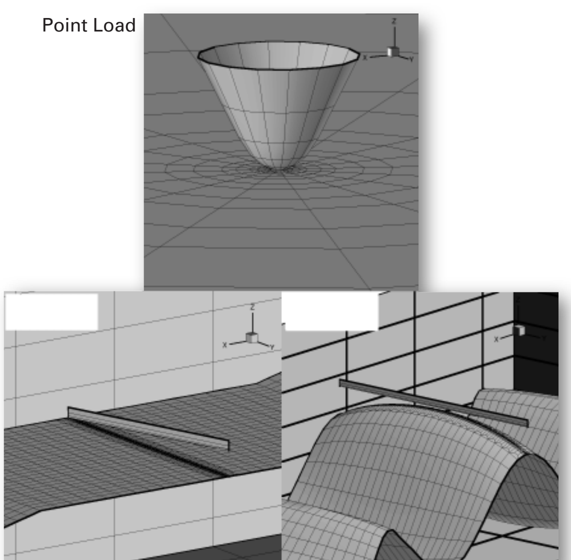

Figure 4: Different initial membrane shapes and tip configurations.

RESULTS AND CONCLUSIONS

The analysis presented in this extended summary is limited to a flat-modeled membrane with a tip of 120 μm (line load). This was accurate enough for the purpose of understanding the effect of the error in Young's modulus (E) and residual stress (σ_0) in the identification process. The pair (E, σ_0) is taken from the input files corresponding to the best matching load-displacement curve. These values are inherent to the material and the structure, respectively. Thus, the variation in these parameters establishes the accuracy of the integrated technique.

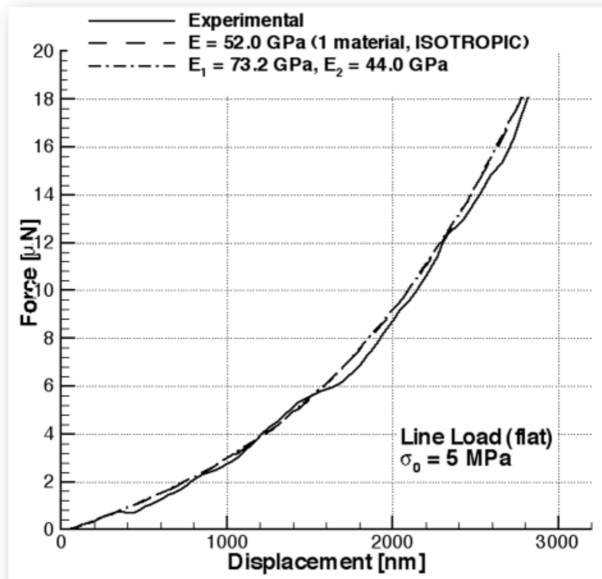

Figure 5: Matching load-displacement curve.

The value of E used in the simulations needs to be modified to take into account the effect of holes manufactured in the aluminum membrane. If the portion of the membrane with holes is considered as an anisotropic homogenized material with modulus E_2 and the borders (no holes) with modulus E_1, the value identified for E differs from the one considering the membrane with no holes. Figure 5, shows the matching load-displacement curve for the line load case. The Young's modulus of the material is E_1=E_{mat}=73.2 GPa. E_{mat} results from a RVE analysis for an E_2=44 GPa (considering the homogenized material to be tetragonal).

A good interpretation of the results makes it necessary to estimate the error of the procedure. Dispersion is estimated by plotting a large number of experimental curves and calculating their deviation from a mean. The error bars, experimentally determined, are shown in Figure 6. Simulations using different values of Young's modulus and residual stress are superimposed to identify the maximum error in E and σ_0 due to experimental uncertainty. It was found that the error in Young's modulus is ± 10 GPa and the error in residual stress is ± 2 MPa.

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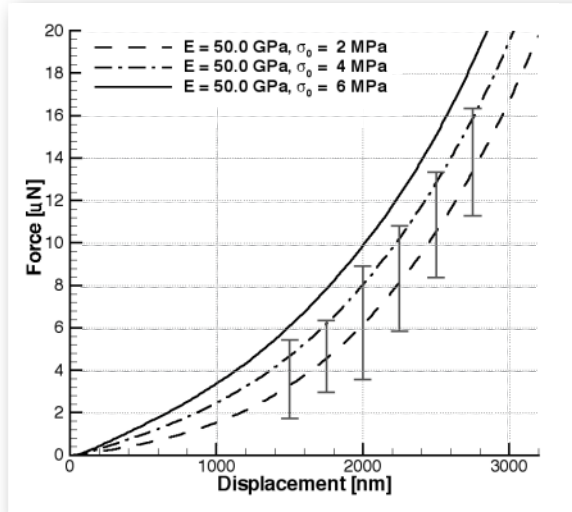

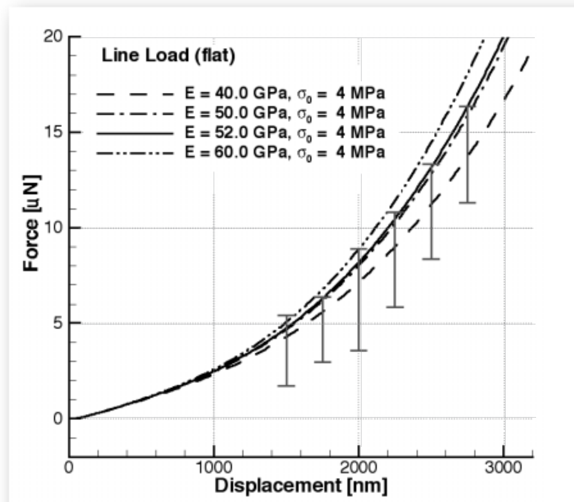

Figure 6: Computed error in Young's modulus (ΔE = ± 10 GPa) and residual stress ($\Delta\sigma_0$ = ± 2 MPa).

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