RELIABILITY TESTING OF POLYSILICON FOR MEMS DEVICES

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Abstract

Mission critical applications of MEMS devices require knowledge of the distribution in their material properties and long-term reliability of the small-scale structures. This project reports on a new testing program at Sandia to quantify the strength distribution using samples that reflect the dimensions of critical MEMS components. The strength of polysilicon fabricated with Sandia's SUMMiT 4-layer process was successfully measured using samples with gage sections 2.5 μm thick by 1.7 μm wide and lengths of 15 and 25 μm. These tensile specimens have a freely moving pivot on one end that anchors the sample to the silicon die and prevents off-axis loading during testing. Each sample is loaded in uniaxial tension by pulling laterally with a flat tipped diamond in a computer-controlled Nanoindenter. The stress-strain curve is calculated using the specimen cross section and gage length dimensions verified by measuring against a standard in the SEM.

The first 48 samples had a mean strength of 2.24 ± 0.35 GPa. Fracture strength measurements grouped into three strength levels, which matched three failure modes observed in post mortem examinations. The seven samples in the highest strength group failed in the gage section (strength of 2.77 ± 0.04 GPa), the moderate strength group failed at the gage section fillet and the lowest strength group failed at a dimple in the hub. With this technique, multiple tests can be programmed at one time and performed without operator assistance at a rate of 20-30 per day allowing the collection of significant populations of data. Since the new test geometry has been proven, the project is moving to test the distributions seen from real geometric features typical to MEMS such as the effect of gage length, fracture toughness, bonding between layers, etch holes, dimples and shear of gear teeth.

Introduction

Understanding and predicting the reliability of polysilicon micromachined MEMS devices requires a thorough knowledge of the distribution in mechanical properties and the effect of stress concentrating features in these devices. Several authors have published work reflecting different strategies to determine the mechanical properties of polysilicon via beam bending [1, 2] and tension testing [3-6]. These efforts have succeeded, but they have not characterized features in MEMS devices most likely to initiate failure. This project developed a technique that utilizes an automated test machine, capable of testing 20-30 samples per day with little operator involvement. The objective is to determine the distribution of mechanical properties in surface micromachined polysilicon ligaments and

Fig. 1. The upper section shows a comb drive spring with dimples and sacrificial oxide cuts bonding the layers together.
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characterize the stress concentrating effect of critical features in MEMS devices such as comb drive springs, hinges, pivots, gear teeth, dimples and etch release holes. Fig. 1 [7] illustrates the small design features that must be characterized before MEMS can be applied in critical applications. A simple spring, shown in the top of Fig. 1 contains multiple dimples to reduce surface friction and sacrificial oxide cuts to join layers.

Technique

Pull-tab samples designed to measure the fracture strength and elastic modulus of polysilicon have been fabricated using Sandia National Laboratories' Ultra-planar Multi-level MEMS Technology (SUMMiT) process. Fig. 2 shows two samples after release. Each sample has a freely moving pivot and a pull-tab, the pivot and pull-tab are connected by a 2 μm wide ligament. The release process allows the samples to rotate about the pivot and the samples must be moved back to the proper position with a probe tip before testing. To conduct a test, the pull-tab end of a sample is engaged by a 35 μm diameter flat tipped diamond using a nanoindenter. The tip approaches the silicon substrate surface centered within the pull-tab end of the sample at a rate of 10 nm/sec until it senses surface contact by a change in indenter column stiffness. Load is increased until the substrate surface deflects 10 nm then the tip moves laterally to engage the pull-tab while the normal force, lateral force and displacement are recorded. The normal force is maintained throughout the test to prevent the conical shaped diamond from being pushed upwards by the pull-tab engagement reaction. Once engaged, the tip continues to move laterally which loads the thin polysilicon ligament in tension. Fig. 3 shows two samples, the one in the foreground has been tested. The samples and recorded force-displacement data are analyzed after testing to calculate the stress-strain response and to identify the sample failure mode.

A total of 48 samples were tested, 25 with 25 μm long gage lengths and 23 with 15 μm long gage lengths. Measurement of the cross-section dimensions is very important for accurate calculation of the stress. With calibration, the sample dimensions can be measured in an SEM to 0.1 microns. The thickness is expected to be very close to nominal, and the width should reflect a 150 nm undercut which is part of the SUMMiT process. The samples measured, on average, 1.8 microns wide and 2.6 microns thick, slightly less than the nominal cross-section dimensions of 2 μm wide by 2.5 μm thick.
Results

Fig. 4 shows load-displacement curves from four separate tests, two from samples with 15 µm gage lengths and two from samples with gage lengths of 25 µm. The load displacement curves show four distinct regions. The first region reflects the indenter tip contacting the surface. The second region reflects the tip sliding along the substrate, maintaining the 10 nm deep surface contact (this requires a normal force of approximately 5 mN). The third region shows engagement with the pull tab and tensile loading. The lateral displacement continues until the sample fractures. Finally, the fourth region shows the post-fracture tip motion until it finishes the 20 µm traverse across the substrate. Fig. 5 shows a small section of one load-displacement graph illustrating the precision of the measurements. Load accuracy is ±50 µN and displacement accuracy is ±50 nm.

In each case, the broken sample is trapped on the end of the indenter tip and can be examined to characterize the failure mode. Three distinct modes were identified in all of the tested samples. The samples with the highest fracture strength failed as intended in the gage section. Those in the intermediate strength group failed at the fillet between the gage length and the pivot end of the sample. The samples with the lowest strength failed in the pivot-ring from an apparent stress concentration of a dimple on the underside of the ring. Samples that show these typical modes are illustrated in Figure 6. The average strength of all the samples was 2.24 GPa with a standard deviation of 0.35 GPa. No size effect was noted between the 15 and 25 micron long samples. The strength of these is 2.24 ± 0.37 GPa and 2.28 ± 0.39 GPa respectively. Considering only the seven samples that failed perfectly within the gage section the average strength is 2.77 ± 0.04 GPa. Fig. 7 is a cumulative probability plot of all the tests.

Discussion

These early results show that this technique will be able to contribute a significant amount of data to assess the reliability of MEMS devices. New designs that have a much stiffer pivot, with gage lengths ranging from 15 to 1000 microns as well as modified designs that incorporate critical MEMS features are currently being fabricated. Future work will also focus on isolating the variation in measurements due to material properties and those due to geometry. Polycrystal elastic finite element
models of these ligaments will focus on characterizing the critical flaws. Elastic Modulus is not
reported in this preliminary investigation since the compliance of the pivot was very large compared to
the samples, and the difference in gage length was not large enough to provide useful information using
a differential stiffness technique [8]. Considering only the tests that failed in the gage section provides a
measurement of strength of \(2.77 \pm 0.04\) GPa. Previous tensile tests [4, 6], without the benefit of a pivot,
and on material from another source, reported strengths of \(1.20 \pm 0.15\) GPa and \(1.45 \pm 0.19\) depending
on sample size. Tests using beam bending techniques [1, 9] have reported strengths of 2.7 to 3.4 GPa.

![Figure 6. Failure modes observed in tensile samples (a) Gage section (b) fillet (c) at dimple in pivot.](image)

![Figure 7. Cumulative probability of failure of polysilicon tensile samples.](image)
Acknowledgments

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

References