Strength of Polysilicon for MEMS Devices

David A. LaVan and Thomas E. Buchheit

Sandia National Laboratories, Materials Performance, Reliability and Aging Department
Albuquerque, NM 87185

ABSTRACT

The safe, secure and reliable application of Microelectromechanical Systems (MEMS) devices requires knowledge about the distribution in material and mechanical properties of the small-scale structures. A new testing program at Sandia is quantifying the strength distribution using polysilicon samples that reflect the dimensions of critical MEMS components. The strength of polysilicon fabricated at Sandia's Microelectronic Development Laboratory was successfully measured using samples 2.5 microns thick, 1.7 microns wide with lengths between 15 and 25 microns. These tensile specimens have a freely moving hub on one end that anchors the sample to the silicon die and allows free rotation. 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.

Fracture strength measurements grouped into three strength levels, which matched three observed failure modes. The samples in the highest strength group failed in the gage section, those in the moderate strength group failed at the gage section fillet and those in 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 characteristic of MEMS, such as the effect of gage length, fracture toughness, bonding between layers, etch holes, dimples and shear of gear teeth.

Keywords: polysilicon, strength, Weibull, distribution, tensile, nanoindenter, MEMS

1. 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 [3-7]. 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 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. Figure 1 [8] illustrates the small design features that must be characterized before MEMS can be applied in critical applications. A simple spring, in the upper left portion of the micrograph, contains dimples to reduce surface friction and sacrificial oxide cuts to join layers.

2. TECHNIQUE

Pull-tab samples designed to measure the tensile fracture strength and Young's modulus of polysilicon have been fabricated using Sandia National Laboratories' Ultra-planar Multi-level MEMS Technology (SUMMiT) process. Figure 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

Figure 1. Dimples and oxide cuts on a comb drive spring.

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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. Figure 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.

Figure 2. Top view of two samples after release. They are straightened before testing.

Figure 3. Two Polysilicon samples. The gage length is 25 μm long, the sample in the foreground has been tested.

A total of 48 samples was 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 μm . The thickness is expected to be very close to nominal, and the width should reflect a 150 nm undercut during the patterning of the polysilicon. The samples measured, on average, 1.8 μm wide and 2.6 μm thick, slightly less than the nominal cross-section dimensions of 2 μm wide by 2.5 μm thick.

Fig. 4. Typical load-displacement graphs.

Fig. 5. Section of load-displacement curve showing initiation of tension test.

3. RESULTS

Fig. 4 shows load-displacement curves from four 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 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. Figure 5 shows a small section of one load-displacement graph illustrating the precision of the measurements. Load accuracy is $\approx 50 \mu\text{N}$ and displacement accuracy is $\approx 50 \text{ nm}$.

In each case, the broken sample is trapped on the end of the indenter tip and remains in place at the end of the test. The fracture surfaces 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.

Figure 6. Failure modes observed in tensile samples: (a) gage section (b) fillet (c) at dimple in pivot.

The average strength of all the samples was 2.24 GPa with a standard deviation of 0.35 GPa. No volume effect was measured between the 15 and 25 μm long samples; the number of samples in each population was small as is the difference in volume. The strength of the shorter samples is $2.24 \pm 0.37 \text{ GPa}$ and the longer samples $2.28 \pm 0.39 \text{ GPa}$. Considering only the seven samples that failed perfectly within the gage section the average strength is $2.77 \pm 0.04 \text{ GPa}$. Figure 7 is a Weibull plot of all the data, including data from the literature for the strength of polysilicon fabricated at MCNC and tested by Yuan and Sharpe [4, 5] in the form of probability of failure, $p_j = (j - 0.5)/n$ [9], versus strength. Figure 8 is a Weibull plot of the same data in the form of $\ln(\ln(1/(1 - P_j)))$ versus $\ln(\text{strength})$ [10]. For comparison, the MCNC samples were 3.5 μm thick, 600 μm wide and 4 mm long.

4. 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 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 [11]. Considering only the tests that failed in the gage section provides a measurement of strength of $2.77 \pm 0.04 \text{ GPa}$. Previous tensile tests [4-6], without the benefit of a pivot, and on material from another source, reported strengths of $1.20 \pm 0.15 \text{ GPa}$ and 1.45 ± 0.19 depending on sample size. Tests using beam bending techniques [1, 12] have reported strengths of 2.7 to 3.4 GPa.

Figure 7. Probability of failure of polysilicon samples.

Figure 8. Weibull distribution of strength data for polysilicon samples.

Analyzing the data using Weibull statistics and assuming a cut-off stress of zero, the probability of failure at or below a given stress, σ , is given by the equation:

$$P(\sigma) = 1 - \exp[-(\sigma / \sigma_0)^m]$$

The Weibull modulus was evaluated by calculating the slope of the data in Figure 8, and σ_0 was the strength in Figure 7 that corresponds to a probability of failure of 0.632. The Weibull modulus for the Sandia samples is 7.2 with $\sigma_0 = 2.4$ GPa. For comparison, the Weibull modulus for the data for the samples fabricated at MCNC is 9.6 with $\sigma_0 = 1.3$ GPa. The Sandia samples exhibit much higher strengths, (perhaps due to the pi and a broader distribution. The broader distribution is believed to be due to the multiple failure modes; results from new samples that are designed to eliminate some of the unexpected failure modes are expected to report a much narrower distribution in strength, with a correspondingly higher Weibull modulus.

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6. REFERENCES

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