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13. ABSTRACT (Maximum 200 words) The research supported under this grant was part of a multi-institution round-robin experiment to determine the elastic modulus and fracture strength of a common material used in micro-electro-mechanical systems (MEMS). Research teams at four institution - Johns Hopkins University, California Institute of Technology, Experiment/Failure Analysis Associates and the University of California, Berkeley - designed unique devices for determining the material properties of interest. All four designs were then fabricated on using the Multi-User MEMS Processes (MUMPs) at MCNC, Research Triangle Park, NC. MUMPs is regularly scheduled polysilicon surface micromachining fabrication service. Specimens were produced on centimeter-square dies at adjacent locations on the wafers. The specimens tested were from the MUMPs 19 and MUMPs 21 runs. Following fabrication, the structures were released and tested at each individual facility. Results were compared at the Spring, 1998 meeting of the Materials Research Society, with the paper published in the MRS Proceedings Volume 518.			
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Final Report
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Overview

The research supported under this grant was part of a multi-institution round-robin experiment to determine the elastic modulus and fracture strength of a common material used in micro-electro-mechanical systems (MEMS). Research teams at four institutions – Johns Hopkins University, California Institute of Technology, Exponent/Failure Analysis Associates and the University of California, Berkeley – designed unique devices for determining the material properties of interest. All four designs were then fabricated on using the Multi-User MEMS Processes (MUMPs) at MCNC, Research Triangle Park, NC. MUMPs is regularly scheduled polysilicon surface micromachining fabrication service. Specimens were produced on centimeter-square dies at adjacent locations on the wafers. The specimens tested were from the MUMPs 19 and MUMPs 21 runs. Following fabrication, the structures were released and tested at each individual facility. Results were compared at the Spring, 1998 meeting of the Materials Research Society, with the paper published in the MRS Proceedings Volume 518.

The Berkeley Research Effort

In order to obtain a statistically significant set of fracture data, there must be a sufficient amount of data to make the results meaningful. The structures used in this work allow a large number of specimens to be tested to failure in a reasonable time. This is possible by testing the material in cantilever bending rather than the more traditional uniaxial tension. The structures used are quite small, only 320 μm by 500 μm , so that a large number of devices can be fabricated on a single die. The fabrication process can be performed using only one mask set, making this technique attractive for testing a wide range of thin film materials, not just those that might be found in traditional MEMS devices. The test structures are on the same length scale and are tested in a mode consistent with the deformation of many mechanical MEMS elements, thus providing information that is directly useful to designers. This device does not, however, allow a direct determination of the stress at failure. Rather, the strain at failure is determined, from which the associated stress may be obtained using Young's modulus.

The central element of the structure to measure the fracture strength of brittle MEMS materials is a shuttle tethered to the substrate by a folded flexure. Attached to the shuttle is an array of cantilever beams that are bent as the shuttle is displaced in-plane by an off-chip probe. As each beam breaks, the end displacement is determined from a video image of the structure. Because the beams are deformed in bending rather than in uniaxial tension, the magnitude of the motion is large and is readily detected using the optics available on the probe station used.

Nonlinear beam theory, including the compliance of the beam support, is then used to calculate the state of strain in the beam as a function of its tip deflection.

An SEM photograph of an undeformed structure is shown in Fig. 1. In this configuration, the probe tip will push the shuttle toward the bottom of the image. The six cantilever beams at first move rigidly with the shuttle, but after a short time contact the pads anchored near their free ends. A contact pad acts to fix the position of that point on the beam, causing the remainder of the beam to bend as the shuttle continues its motion. A scanned video image of the fracture test device during testing is shown in Fig. 2. Notice that in this image, the shortest two beams have already failed, and the longer beams are highly deformed. Figure 3 shows a close-up image of one of the beams as it is being bent. Figure 4 shows a close-up image of one of the beams and its contact pad prior to testing.

The deformed shape at failure is recorded with a digital camera and matched with a nonlinear analysis of the elastic deformation of the beam to extract the strain at failure. Knowledge of Young's modulus is required to determine the strength, and this is determined in two separate experiments — one in which the out-of-plane load-deflection of short cantilever beams is measured and one in which the natural frequencies of lateral resonant structures are measured.

Comparison of Round-Robin Results

Table I is taken from the MRS Paper reporting the results of the round-robin experiment. Comments in this paper are given below.

Table I. Results of Round-Robin to determine
The Elastic Modulus and Fracture Strength of MUMPs Polycrystalline Silicon

	Berkeley - Cantilever Bending	Caltech - Tension	Failure Analysis - Notched Bending	Hopkins - Tension	Hopkins - Tension
Thickness (microns)	1.9	1.9	2.0	1.5	3.5
Etch Time (Minutes) Note 1	9	16	2.5	9	9
Number Tested Note 2	90	3	12	19	14
Young's modulus (GPa)	174	132	137	136 Note 3	142
Standard Deviation	20	-	5	14	25
Coefficient of Variation	11%	-	4%	10%	18%
Strength (GPa)	2.8	-	2.7	1.3 Note 3	1.3
Standard Deviation	0.5	-	0.2	0.2	0.1
Coefficient of Variation	18%	-	7%	18%	8%

Note 1 - The standard etch release time at MCNC is 9 minutes. Failure Analysis released their own specimens with a shorter time to avoid damage to the electrostatic fingers. Caltech used a longer etch time to release the electrostatic paddle.

Note 2 - The number of specimens is approximate since both strength and modulus were not determined from every specimen.

Note 3 - Incorrect values were reported at the MRS meeting; the wrong thickness was used.

A generally accepted value of Young's modulus for polysilicon is 160-170 GPa. Greek, et al. report 165 GPa and 172 GPa for polysilicon that they produced. Mullen, et al. compute an average value of 160 GPa for a randomly oriented polycrystal of polysilicon. Sharpe, et al. measured 169 GPa for polysilicon from five MCNC MUMPs runs.

The Berkeley modulus measurements, using both in-plane and out-of-plane deformations, agree well with the above values. The other three values are considerably lower, but agree with each other. They were measured in the plane; however, different stress/strain fields were imposed.

Lee et al. measured Young's modulus via resonance methods as a function of doping and annealing. The texture of the 2 micron thick structures varied as did the modulus, which ranged from 154 to 167 GPa. This suggests, quite reasonably, that the modulus depends upon the manufacturing process. The effects of the many variables associated with depositing and processing polysilicon must be studied with both microstructural examination and mechanical testing.

Tsuchiya et al. reports strengths (measured in tension) of 2.0 - 2.8 GPa for both doped and undoped 2 micron thick polysilicon films of various widths and lengths. The Berkeley and Failure Analysis strengths reported here are consistent with that range, even though they were determined using specimens with relatively small regions of high stress.

Greek et al. report an average strength in tension of 1.2 GPa, but later results show 1.8 GPa. They attribute this difference to an improved etch release process. Their first result is in line with the Hopkins measurements.

Tsuchiya concludes that fracture originates on the edges of specimens. That may explain the difference between the strengths measured here. The tensile specimens have a larger surface area (and volume) exposed to the maximum stress than do the bending specimens with their regions of high localized stress.

This is the first set of experiments in which a common polysilicon has been tested by different methods. Other approaches, such as simpler resonant structures for modulus testing and bulge testing for biaxial stressing, were not included because of the limited nature of this initial effort.

At this stage, one cannot conclude that one test method is more suitable than the others. (One cannot even conclude what the Young's modulus and strength of MCNC polysilicon are.) Although research into mechanical properties of MEMS materials is increasing dramatically, it is clear that a preferred test procedure has not yet emerged. Expanded Round Robins could make a major impact.

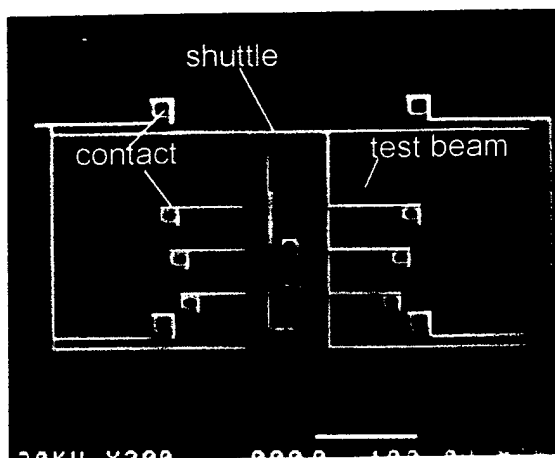


Figure 1: SEM micrograph of fracture strength test structure.

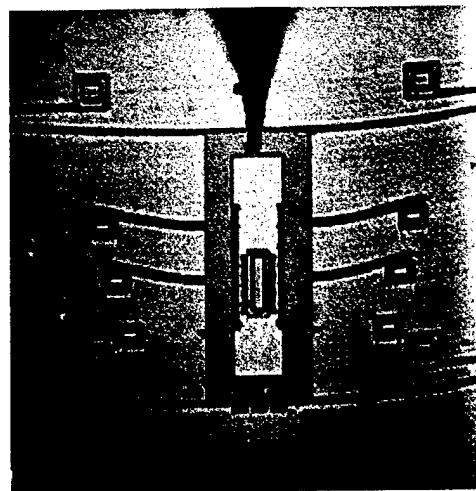


Figure 2: Scanned video image of fracture strength test structures during testing.



Figure 3. Berkeley specimen. The cantilever beam is $1.9\text{ }\mu\text{m}$ thick and $2.8\text{ }\mu\text{m}$ wide. The distance between the shuttle at the bottom to the fixed stop at the top is $70\text{ }\mu\text{m}$. The shuttle has displaced $21.6\text{ }\mu\text{m}$ to the right in this photo.

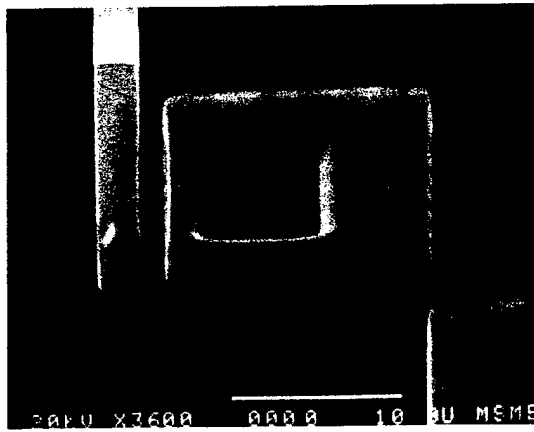


Figure 4: SEM micrograph showing the initial gap between free end of cantilever and anchored contact.