MECHANICAL PROPERTIES OF DIFFERENT POLYSILICONS

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ABSTRACT

Polysilicon materials from three different suppliers were tested in tension to determine their Young's modulus and strength. The modulus of polysilicon from Cronos was 158 ± 8 GPa and its strength 1.56 ± 0.25 GPa, and the material from Sandia National Laboratories showed 157 ± 6.5 GPa and 3.09 ± 0.18 GPa. Two polysilicons from Standard MEMS Inc. showed 164 ± 11.2 GPa and 152 ± 10.0 GPa for modulus values and 2.08 ± 0.35 GPa and 2.00 ± 0.25 GPa for strengths. Polysilicon is therefore similar to most structural materials in that its modulus is essentially constant, but its strength can depend on processing.

INTRODUCTION

Structural materials of a certain class, e.g. aluminums, have essentially the same Young's modulus but different strengths depending upon manufacturing processes. One wonders if the same is true for materials used in MEMS, but test methods have not yet been standardized enough to permit answers to these kinds of questions. The authors have developed tensile test techniques and procedures for determining Young's modulus and strength of polysilicon, which they have used to test material from three different sources.

Mechanical property tests have previously been conducted on polysilicon prepared under different conditions; however, these materials were all prepared in each researcher's facility. Koskinen et al [1] measured both Young's modulus and strength by a clever tensile method. They tested polysilicons that were heat treated to produce various grain sizes and found little variation in the modulus. However, the strengths increased from 2.69 GPa to 3.37 GPa when the material was oxidized. Biebl et al [2] measured the strength in tension of polysilicons with various doping levels and recorded values ranging from 2.11 – 2.84 GPa. In a parallel work, Biebl et al [3] used resonant

microstructures to determine Young's modulus of polysilicons with various doping and heat treatments and obtained values from 135 to 168 GPa. Tsuchiya et al [4] tested polysilicon subjected to various processing conditions and obtained values ranging from 1.8 – 3.7 GPa depending upon the annealing temperature.

Specimen design is the key to any mechanical test method, and that is presented in the next section along with information on the material tested. That is followed by a description of the latest version of test techniques and procedures. The results of the measurements of Young's modulus and strength of the three materials comprise the heart of the paper, and that section is followed by concluding remarks.

SPECIMENS AND MATERIALS

An outline drawing of the tensile specimens is shown in Figure 1; these four specimens would be a portion of a one-centimeter square die.

Figure 1. Drawing of the four tensile specimens.

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The top end is fastened to the silicon wafer, and the rest of the specimen is released by etching away an underlying layer. The test section is the straight portion, which tapers into the ends with a large radius of curvature. The grip end, which contains etch holes, is anchored at four corners to prevent damage as the die is handled. Those anchors are cut prior to testing. The nominal dimensions of the test sections of the specimens were 6 or 20 μm wide and 250 or 1000 μm long.

Polysilicon specimens were obtained from MCNC (now Cronos) on the MUMPs 25 run of July 1998. Specimens prepared by a similar process came from Standard MEMS Inc. In both cases, tensile specimens that were 1.5 μm , 2.0 μm , and 3.5 μm thick were supplied – the latter being a two-layer combination. Sandia National Laboratories provided two-layer specimens that were 2.5 μm thick.

TEST PROCEDURES

Tensile test techniques and procedures have been developed at Johns Hopkins University, which are applicable to thin-film materials. Strength is relatively easy to measure, but Young's modulus is more difficult to determine. Strain can be measured directly on the specimen by laser interferometry if the specimen is wide enough (20 microns or wider), but for smaller specimens Young's modulus must be determined from force-displacement records. Details of the test methods are given in [5] with a short description presented here.

Figure 2. Schematic of the test system.

Figure 2 is a schematic of the test system. The die carrying the specimens is glued to a holder, which is then mounted to a five-axis piezoelectric stage. That stage is used to align each specimen relative to the electrostatic probe so that the specimen will be pulled straight along its tensile axis. That alignment is determined visually with a stereo microscope looking perpendicular to the specimen and a low-power telemicroscope looking from the side. The probe, a silicon strip with an insulating nitride layer, is mounted into the 100-gram (0.98 N) load cell, which is attached to a uniaxial piezoelectric

stage. Overall displacement of the system is measured with a capacitance-based probe. After the specimen is gripped by the electrostatic probe (at ~ 150 volts), the uniaxial stage is activated and the force and displacement recorded by a laboratory computer.

A representative record is shown in Figure 3 for a relatively large 3.5 by 20 by 1000 μm specimen. Smaller specimens often show an initial curve in the force-displacement plot; in those cases only the upper linear region is used for modulus determination.

Figure 3. Force-displacement plot from a Cronos specimen 3.5 μm thick, 20 μm wide, and 1000 μm long. The specimen shows linear behavior until it breaks; the force reading after breaking is shown.

The test system is a series of linear springs consisting of the load cell, the straight tensile section, and the two grip ends. This is explained in [5], and the equation describing the system is

$$1/S = (1/E) \times (L/A + \beta w/A) + 1/k_l$$

where S is the slope of the force-displacement plot; E is of course Young's modulus; L , A , and w are the length, area, and width of the straight tensile section; β is a factor accounting for the grip-end shapes [5]; and k_l is the stiffness of the load cell.

The quantity $D = (L/A + \beta w/A)$ describes the geometry and size of a specimen and can be regarded as the independent variable for a set of specimens of different sizes as tested here. A plot of $1/S$ versus D will show points lying on a straight line if the size of the specimen does not affect the value of Young's modulus. The inverse of the slope of such a plot yields the Young's modulus of the material and the intercept gives the inverse of the stiffness of the load cell. Figure 4 shows such a plot for all four sets of materials. From this kind of plot, one can determine a 'global' modulus of the material from its slope and the load cell stiffness from its intercept. Further, the fact that the data points tend to lie along a straight line indicates that the measurements are independent of the specimen size.

Figure 4. Inverse stiffness versus dimension factor for polysilicon specimens from three different sources. The specimens with the largest dimension factor are 1.5 μm thick, 3.3 μm wide, and 1000 μm long. The ones with the smallest dimension factor are 3.5 μm thick, 15.7 μm wide, and 250 μm long.

RESULTS

For each of the four materials (counting two for SMI), the stiffness of the load cell was taken from Figure 4 and used to compute the Young's modulus of each specimen. The stiffness of the system should be the same

(indeed they nearly are at $8.64, 8.88, 8.49$, and $8.64 \times 10^{-3} \text{ N}/\mu\text{m}$), but there are slight differences for each of the mounted dies. Those modulus values are averaged and plotted in Figure 5; the number of individual specimens tested is shown.

Figure 5. Average values $\pm$ one standard deviation of Young's modulus for the four materials.

The average values in Figure 5 are essentially the same as obtained from the slopes in Figure 4, but this shows the scatter in the results. The figure shows little difference in the modulus values, but Student 't' tests show that there are differences between both the SMI materials and between them and the Cronos or Sandia materials at near the 100% confidence level.

However, the strengths are different as Figure 6 shows. The Sandia material is considerably stronger; in fact, it is so strong that many specimens could not be broken in the smooth test section.

Figure 6. Average values $\pm$ one standard deviation of strengths for the four materials.

DISCUSSION

These results show polysilicon behaves as a typical structural material. Young's modulus is basically a constant, and the strength can be different depending upon the manufacturing process. From a materials science viewpoint, this makes sense. Young's modulus depends upon interatomic forces, but strength depends on larger microstructural factors.

The modulus values are indeed different as Figure 5 shows, but the largest variation is between the two SMI materials and that is a difference of 7.6%. In designing a new MEMS device, one would question whether it is feasible to know the final dimensions and boundary conditions to a greater precision.

Strength is another story; there is almost a factor of two difference. This difference is enough to be important in the design and manufacture of MEMS.

This is the first direct comparison of mechanical properties of polysilicon from different manufacturers and perhaps raises more questions than it answers. Mechanical test methods are developing to the point where comparisons of properties can be made with some confidence. The questions of why these strength differences occur and (perhaps more important) how materials can be processed to achieve desired properties can now be addressed in future research.

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