Out-of-plane microstructures using stress engineering of thin films

Chia-Lun Tsai and Albert K. Henning

Thayer School of Engineering, Dartmouth College, Hanover, NH 03755-8000

ABSTRACT

A new method is presented to fabricate out-of-plane microstructures using traditional planar micromachining technology. Composite LPCVD polysilicon/silicon nitride beams are fabricated to study this concept. Polysilicon films ranging from 0.5 µm to 1.3 µm, and silicon nitride films ranging from 150 to 450 nm, were used to fabricate various thickness ratios of composite out-of-plane microstructures. Upon release, these planar structures take on three-dimensional shapes, due to the bending moment caused by inherent internal stresses in the thin films. These Stress Engineered 3D Micro-Structures (SEMS) open the path to novel microstructures. This paper presents a design theory for SEMS, describes the fabrication process, and discusses the results of initial experiments.

Keywords: stress engineered 3D micro-structures, SEMS, thin-film stress, LPCVD polysilicon, LPCVD silicon nitride, out-of-plane microstructures, micro-cantilevers.

1. INTRODUCTION

The field of micro-electromechanical systems (MEMS) is growing fast. Worldwide sales of devices based on MEMS may reach eight billion dollars by the year 2000. Micromechanical structures are currently being investigated for a wide variety of applications because of their potential to achieve low cost and high performance products. The uses of silicon as a mechanical material have been previously summarized[1]. Surface micromachining technology makes possible fabrication of diaphragms, beams, micromotors, microactuators and resonators. Polysilicon and silicon nitride films in particular can be used as mechanical materials to create in-plane, self-adjusting microstructures released from the substrate through etching of sacrificial layers[2].

Continuing technical barriers - such as microassembly issues, and the process development required to build three-dimensional microstructures - must be surmounted in order to achieve more complex MEMS designs. So far, traditional surface micromachining technology is suitable mostly for making planar microstructures. In this work, we describe a means to create out-of-plane microstructures by engineering the stress between thin films of polysilicon and silicon nitride.

The usual practice in MEMS has been to minimize or eliminate residual stresses in thin films. These stresses have been studied in various applications, using a variety of measurement methods[3-6]. For our purposes, we view residual stress from the opposite direction, as an attractive feature instead of a detrimental problem. That is, we deliberately employ differential stresses in two thin films to effect out-of-plane microstructure. In this study, we have used polysilicon and silicon nitride thin films for this purpose. The polysilicon deposition conditions are selected to obtain a compressive residual stress[7-9]. Stoichiometric silicon nitride films are highly tensile[2]. Our study makes use of internal stress differences between polysilicon and silicon nitride films to bend microstructures into desired three-dimensional shapes. By dissolving sacrificial materials (in our case, deposited silicon dioxide), planar microstructures under stress are released to form intentional 3D shapes. Accurate estimates of the internal stresses between films facilitates the design of predictable SEMS shapes upon release.

Our SEMS test structures use a cantilever design composed of patterned silicon nitride stripes atop patterned polysilicon microcantilevers to study this concept. Figure 1 shows a schematic of a cantilever SEMS and defines the geometric variables.

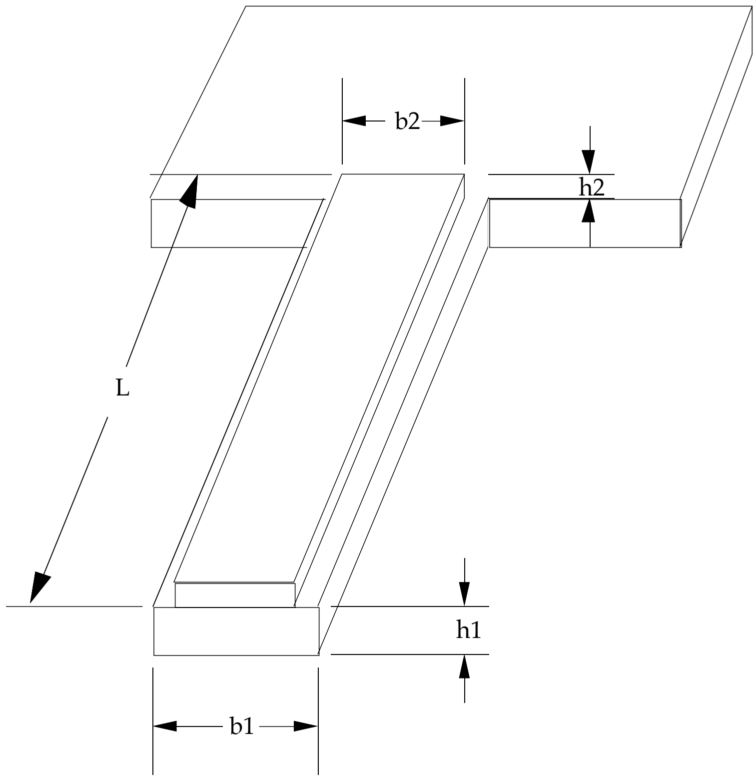


Fig. 1. Perspective view of a cantilever SEMS.

2. THEORY

To derive the model, we follow assumptions used in previous work[2]. Figure 1 shows a microcantilever beam composed of two materials with residual stresses σ_1 and σ_2, and Young's modulus E_1 and E_2. Other important geometric parameters are film thicknesses h_1 and h_2, widths b_1 and b_2, and the cantilever length L. The analysis of this model is similar to that for bimetallic cantilever structures[4].

Figure 2 shows the forces and moments on the two materials due to their internal stresses. These stresses over the microcantilever cross-section can be reduced to force balance and moment balance equations for the static case.

$$P_1 = P_2 = P \tag{1}$$

$$\frac{P(h_1+h_2)}{2} = M_1 + M_2 = M \tag{2}$$

Instead of calculating the moment-curvature relations for each material, an equivalent beam strength, $(EI)_{equiv,}$ is calculated in the following manner. To calculate the inertia, we first use the equivalent width technique to transform a bi-material beam into a single material beam as shown in Figure 3.

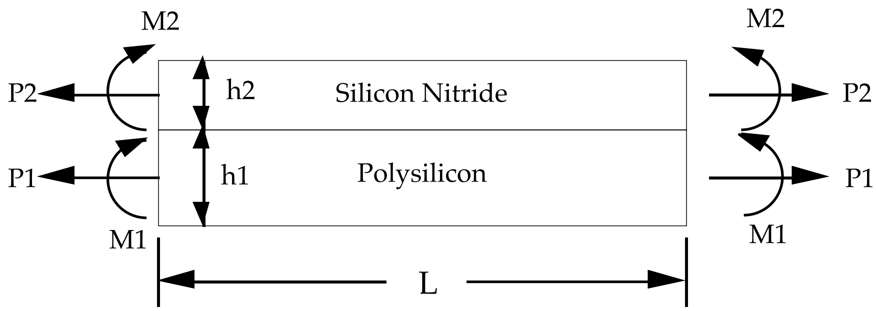


Figure 2: Forces and moments acting on the cross-section of a segment length of the SEMS microcantilever.

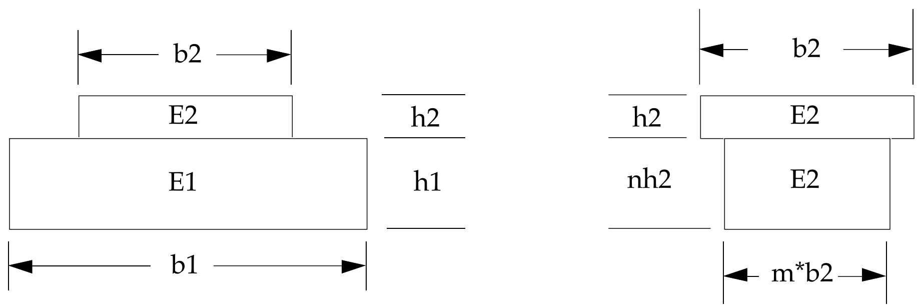


Figure 3: Schematic cross-sections of the SEMS microcantilever. Left: the actual cantilever. Right: the cantilever redrawn using the equivalent width technique.

The moment of inertia is then derived from the parallel axis theorem[10]:

$$I = \frac{1 + 4m^* n + 6m^* n^2 + 4m^* n^3 + m^{*2} n^4}{12(1 + m^* n)} b_2 h_2^3 \tag{3}$$

where $m^* = mo$, $m = E_1/E_2$, $o = b_1/b_2$ and $n = h_1/h_2$.
We can define the equivalent beam strength as:

$$(EI)_{equiv} = E_2 \frac{1 + 4m^* n + 6m^* n^2 + 4m^* n^3 + m^{*2} n^4}{12(1 + m^* n)} b_2 h_2^3 \tag{4}$$

From beam theory,

$$M = \frac{(EI)_{equiv}}{r} \tag{5}$$

where r is the radius of curvature of the beam.

$$P = \frac{2\,(EI)_{equiv}}{r(h_1 + h_2)} \tag{6}$$

Therefore, using (2) and (5), we can obtain a relation between the stress induced internal force and the curvature radius. We assume there is no slip at the interface of the thin films. If the normal strain of materials 1 and 2 is assumed to be the same, then:

$$\frac{\sigma_1}{E_1} + \frac{P}{E_1 h_1 b_1} + \frac{h_1}{2r} = \frac{\sigma_2}{E_2} - \frac{P}{E_2 h_2 b_2} - \frac{h_2}{2r} \tag{7}$$

Using the definitions of P in (6), and of $(EI)_{equiv}$ in (4), the expression for the curvature r may be derived:

$$\frac{1}{r} = \frac{6n(1+n)(m^{*}\sigma_2 - \sigma_1)}{h_2 E_2 [K + 3m^{*}n(1+n^{2})]} \tag{8}$$

where $K = 1 + 4m^{*}n + 6m^{*}n^{2} + 4m^{*}n^{3} + m^{*2}n^{4}$.

From a measurement perspective, the end deflection of a cantilever perpendicular to the pre-released position for a given length L is obtained from trigonometry (see Figure 4). With this radius of curvature given, the end deflection perpendicular to the pre-released position for a given length L can also be obtained from trigonometry:

$$\delta = r(1 - \cos(L/r)) \tag{9}$$

In practical terms, we measure the deflection of our cantilevers for given values of the cantilever thin film widths, thicknesses, and lengths. We compare the measured deflections to those calculated using (9), presuming certain values of stress in the polysilicon and silicon nitride thin films.

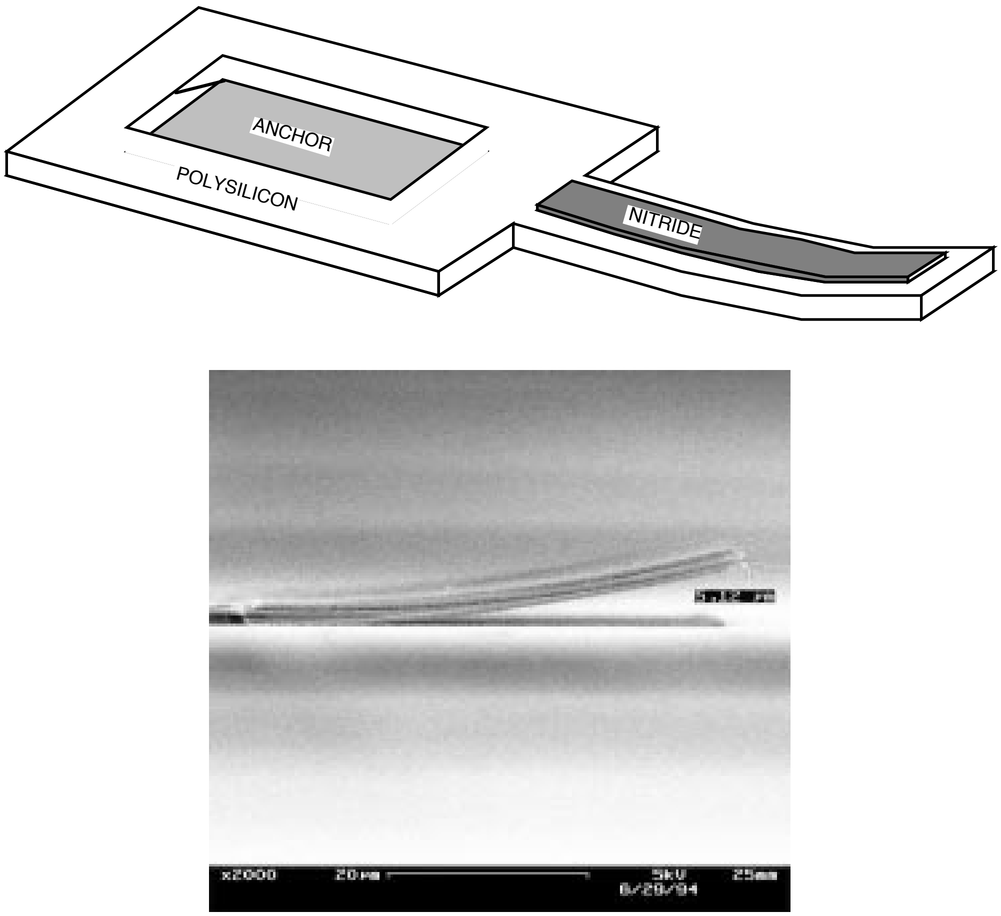


Figure 4. Upper: Schematic representation of the Stress-Engineered Micro-Structure (cantilever). Lower: Demonstration of the displacement measurement methodology using SEM micrographs of our thin film cantilevers after release.

3. FABRICATION

Mask design was accomplished using the layout tool *magic*. Fabrication of test structures was executed using the facilities of the Microsystems Technology Laboratory at the Massachusetts Institute of Technology.
A scheme of the fabrication process is shown in Figure 5. Three masks were needed to fabricate the polysilicon/nitride beam structures. The process began by growing 500 nm of thermal oxide, then passivating this layer with a 150 nm thick LPCVD silicon nitride layer. Next, a 1 µm thick LTO silicon dioxide layer was deposited and patterned using 5:1 buffered hydrofluoric acid (BHF). This sacrificial layer defined the anchors for the cantilever beams.

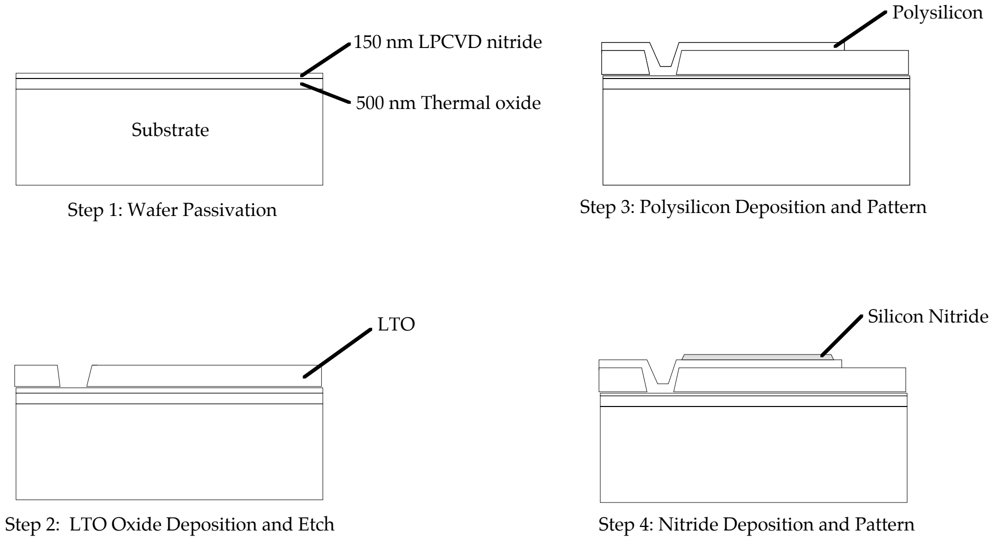


Figure 5: Schematic of the micro-cantilever fabrication process.

Three thicknesses of undoped LPCVD polysilicon, ranging from 0.5 to 1.3 µm, were deposited at 600 ˚C. Next, a two hour 1000 ˚C anneal was performed to reduce the stress in the polysilicon film[11]. The polysilicon film was patterned using photoresist masking and reactive ion plasma etching.

Three thicknesses of LPCVD silicon nitride, 150 nm, 300 nm and 450 nm, were then deposited. These nitride layers were also patterned and plasma etched.

At this stage, nine groups of wafers with various polysilicon/nitride thickness ratios had been completed (Table I). The wafers were stripped of photoresist, cleaned and diced.

To release the cantilever structures mechanically from the substrate, each die was dipped into concentrated (49%) HF, rinsed with DI water, and then rinsed in isopropyl alcohol. Finally, each die was baked to dry in a 120 ˚C oven.

Table I. Experimental Matrix of Polysilicon/Silicon Nitride Film Thickness Ratios

Polysilicon/Nitride Ratio	Nitride=150nm	Nitride=300nm	Nitride=450nm
Poly=0.5µm	n=3.33	n=1.66	n=1.11
Poly=1.0µm	n=6.67	n=3.33	n=2.22
Poly=1.3µm	n=8.67	n=4.33	n=2.89

4. EXPERIMENTAL RESULTS

Figures 6, 7, and 8 are SEM micrographs of released cantilever structures. Three different thicknesses of polysilicon and silicon nitride yield the experimental matrix shown in Table 1.

Typical residual stress values for silicon nitride are 1.0 GPa, and -180 Mpa for undoped LPCVD polysilicon. Young's modulus for silicon nitride and polysilicon are 290 GPa and 160 Gpa[8,9,11]. These values were used to calculate the theoretical deflection value in (9).

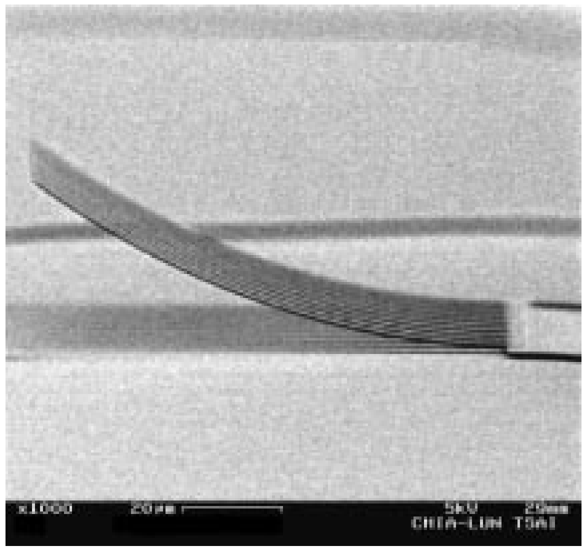
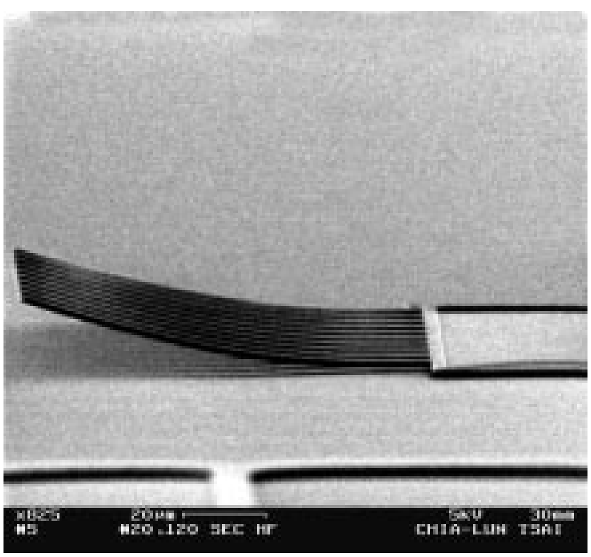


Figure 6. SEM picture of a 100 μm long cantilever. Polysilicon thickness is 0.5 μm, and silicon nitride thickness is 150 nm.



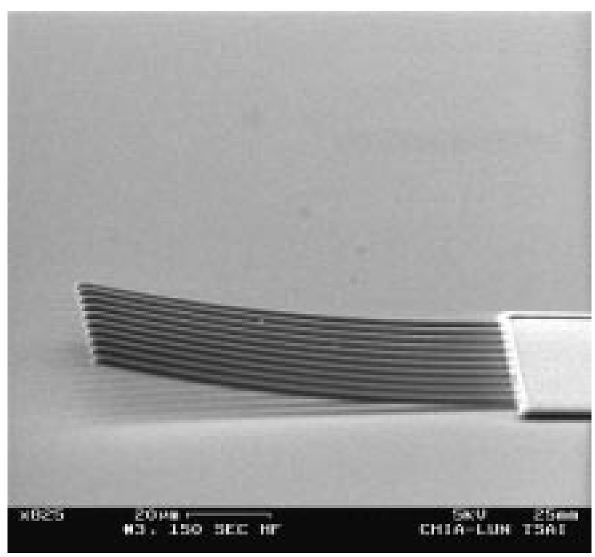


Figure 7 (Left). SEM picture of a 100 μm long cantilever. Polysilicon thickness is 1.0 μm, and silicon nitride thickness is 450 nm.
Figure 8 (Right). SEM picture of a 100 μm long cantilever. Polysilicon thickness is 1.3 μm, and silicon nitride thickness is 450 nm.

Figure 9 plots the deflections for 100 μm and 50 μm cantilever beams versus the ratio of the polysilicon/nitride film thicknesses, n, for three different polysilicon film thicknesses. The characteristic peaks of the measured data are in good agreement with theoretical estimations. The peaks can be explained by looking at the limits of the thickness ratio, n. As n goes to zero or infinity, the composite beam becomes a single material beam, and thus will not deflect. All three polysilicon films show increased deviation from the theory as the thickness ratio, n, increases.

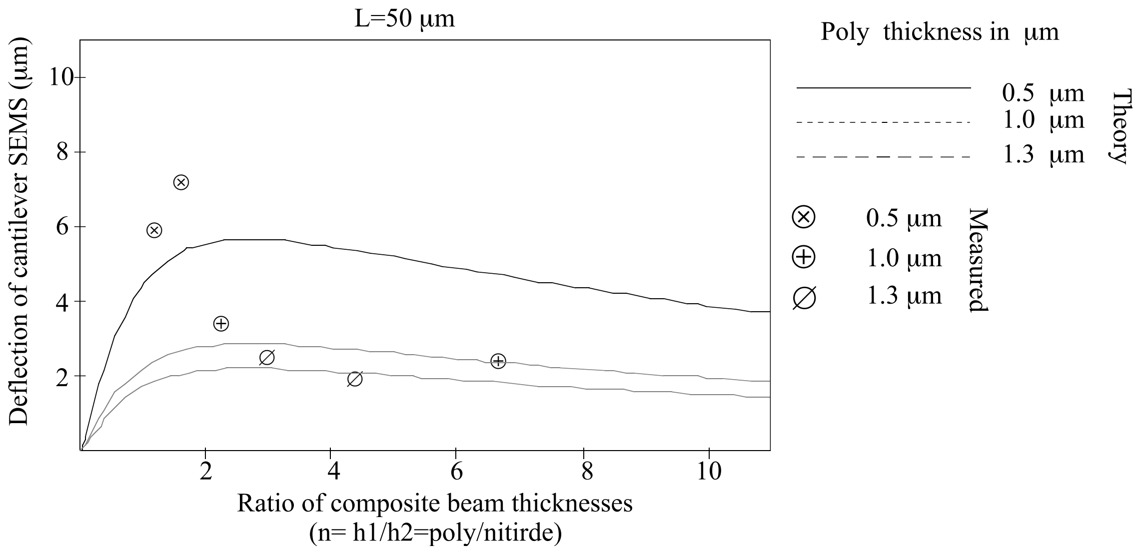


Fig. 9 Plot of measured and calculated deflection of 50 μm long cantilevers versus polysilicon/nitride thickness ratio (n)

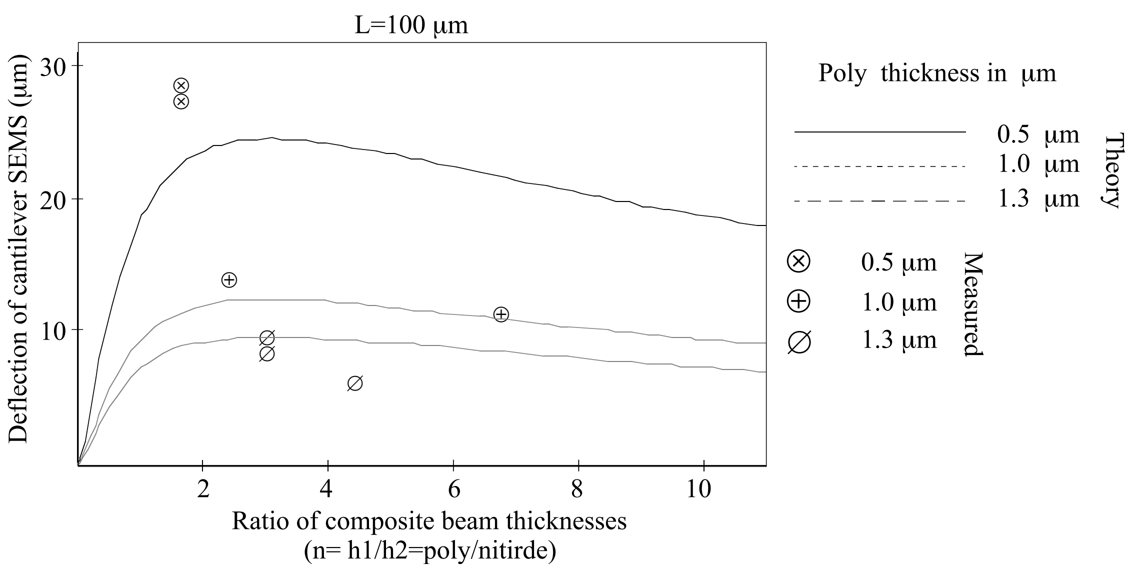


Fig. 10 Plot of measured and calculated deflection of 100 μm long cantilevers versus polysilicon/nitride thickness ratio (n)

5. DISCUSSION

Judy, *et al.* first used the internal stress between polysilicon and silicon nitride layers to fabricate self-adjusting microstructures[2]. These 0.3 µm thick microstructures made use of residual thin film stresses to reduce inter-component clearances, or to apply preloads in micromechanical systems. Their structures were in-plane, since they relied on sidewall depositions of polysilicon and silicon nitride. Because of this sidewall nature, their structures had equal values of b_1 and b_2. Our vertical structures have non-uniform values of b_1 and b_2. As a consequence, our theoretical analysis has been modified (see Figure 3), using the factor $o=b_1/b_2$. This modification led to improved agreement between experiment and theory, compared to the results in Ref. 2.

We observe consistent deflections for these out-of-plane microstructures across each wafer. Also, longer and wider microcantilevers need more time in the HF solution in order to be released. This extra time often leads to overetching of smaller structures. For example, after enough time to release 100 µm microstructures, 5 and 10 µm size cantilevers were often overetched due to extended HF exposure. Polysilicon 'stringers' were observed post-release along the length of cantilevers under certain conditions of underetch during polysilicon etching.

Etch sensitivity has important ramifications for our theoretical calculations and the analysis of measurement errors. The extraction of Young's modulus has been shown to be sensitive to the third power of the thin film thickness in cantilever structures, and in fixed-fixed beam structures[6]. Conversely, our model predictions will be sensitive to changes in the assumed values of Young's modulus in our films, and in the measured film thicknesses compared to the intended or designed thicknesses.

We have modified the model of Ref. 2 to include the effects of non-uniform film width. Figure 11 compares our model to that of Ref. 2. Our model shows peaking at lower values of the poly/nitride thickness ratio n, consistent with our experimental observations.

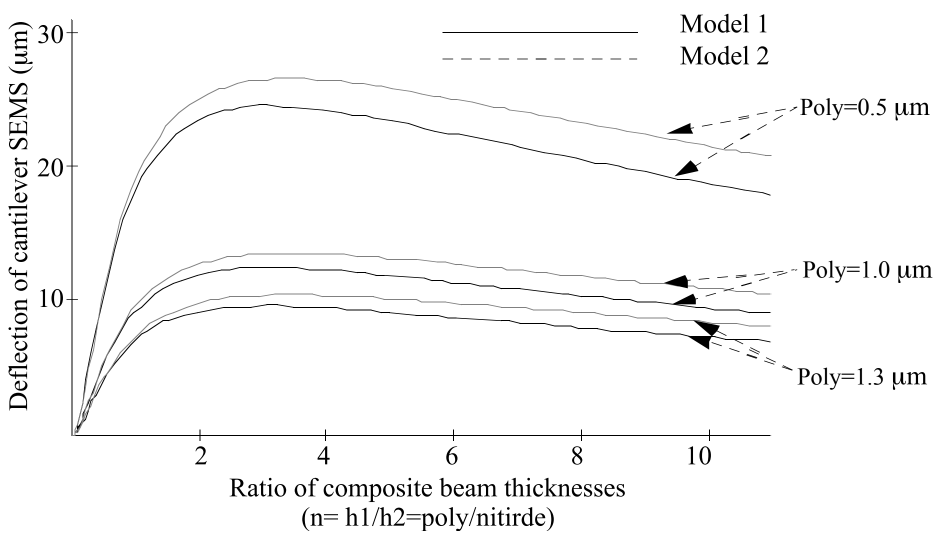


Figure 11. Comparison of calculations of deflection based on our model, and the model of Ref. 2.

6. CONCLUSIONS

The tendency of stress and strain to cause deformation in thin films has frequently been a source of difficulty in the fabrication of microelectromechanical devices. We have attempted to turn these tendencies to advantage, by designing and fabricating cantilever structures with intentional, out-of-plane curvature. Relatively large out-of-plane deflection can be obtained using the combination of zero-stress polysilicon, and high-stress silicon nitride. Our experiments include a range of different cantilever widths, and polysilicon and silicon nitride thicknesses. Within the uncertainties of the experiment, the measured and theoretical results agree reasonably well. Based on the success of these experiments, we are pursuing new opportunities for microsensors and microtransducers.

7. ACKNOWLEDGEMENTS

This work was supported by an Analog Devices, Inc. Career Development Professorship Grant to one of us (AKH), as well as research grants from Analog Devices. The authors acknowledge with gratitude the invaluable assistance of the faculty, staff and students of the Microsystems Technology Laboratory of the Massachusetts Institute of Technology (especially L. Cordes, O. Hurtado, E. Jansen, and M. Schmidt) during the fabrication phase of this work.

8. REFERENCES

1. Kurt E. Petersen, "Silicon as a mechanical material," *Proc. IEEE*, Vol. 70, no. 5, pp. 420-457, May 1982.
2. Michael W. Judy, Young-Ho Cho, Roger T. Howe, and Albert P. Pisano, "Self-Adjusting Microstructures (SAMS)," *Proc. IEEE Micro Electro Mechanical Systems,* pp. 51-56, Nara, Japan, Jan. 1991.
3. Koji Ikuta, Ken Hirowatari, "Real Three Dimemsional Micro Fabrication using Stereo Lithography and Metal Molding," *Proc. IEEE MEMS Workshop*, Florida, USA, pp. 42-47, Feb. 1993.
4. H. Muro, H. Kaneko, S. Kiyota and P. J. French, "Stress analysis of SiO2/Si bi-metal effect in silicon accelerometers and its compensation," *Sensors and Actuators*, Vol. A34, pp. 43-49, 1992.
5. S. D. Senturia, "Microfabricated structures for the measurement of mechanical properities and adhesion of thin films," Transducers '87, *Rec. of the 4th Int. Conf. on Solid-State Sensors and Actuators*, pp. 11-16, 1987.
6. P. Osterberg, "Electrostatically Actuated Microelectromechanical Test Structures for Material Property Measurement." Ph.D. Dissertation, Massachusetts Institute of Technology, 1995 (unpublished).
7. R. T. Howe and R. S. Muller, "Stress in polycrystalline and amorphous silicon thin films," *J. Appl. Phys.*, Vol. 54, pp. 4674-4675, 1983.
8. J. Huang, P. Krulevitch, G. C. Jognson, R. T. Howe, and H. R. Wenk, in *Polysilicon Thin Films and Interfaces, Mat. Rec. Soc. Symp. Proc.,* Vol. 182, pp. 201-206, 1990.
9. O. Tabata, K. Kawahata, S. Sugiyama, and I. Igarashi, "Mechanical property measurements of thin films using load-deflection of composite rectangular membrane," *Proc. IEEE Micro Electro Mechanical Systems,* pp. 152-156, Salt Lake City, Utah, Feb. 1989.
10. Joseph H. Faupel and Franklin E. Fisher, "*Engineering Design,*" B18, John Wiley &Sons, New York, 1981.
11. H. Guckel, D. W. Burns, H. A. C. Tilmans, D. W. Deroo and C. R. Rutigliano, "Mechanical properties of fine grain polysilicon, the repeatablity issue," *Tech. Digest IEEE Solid-State Sensor and Actuator Workshop.* Hilton Head Is., SC, pp.96-99, June 1988.