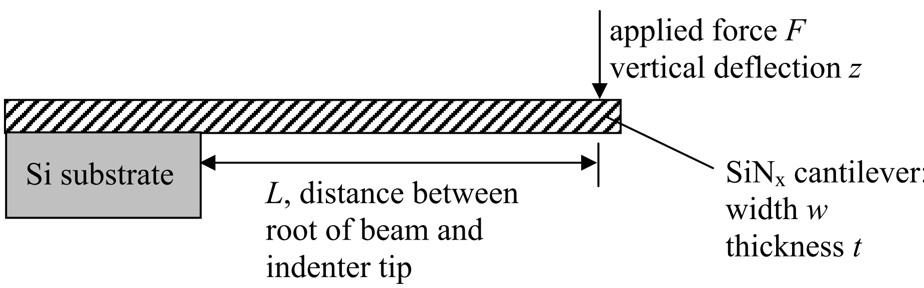
Notes on MEMS lab testing and data analysis

This document describes the data available to you for analysis, summarizes approaches that could be used to analyze the data, and provides additional information that should help you interpret your results.

1. Estimating Young's modulus from the deflection of cantilevers

Here is a longitudinal cross-section of a silicon nitride cantilever:



Where E is Young's modulus, v is Poisson's ratio and $I = wt^3/12$, we have

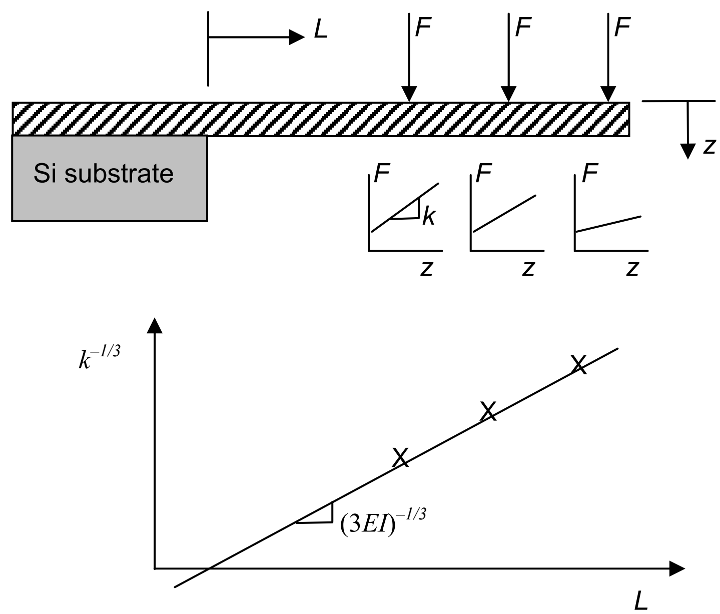
$z = FL^3/3EI$ for a long narrow beam, or
$z = (1- v^2)FL^3/3EI$ for a plate.

Three cantilevers were tested, with a load F being applied to each cantilever at three precisely separated locations in turn. The data are contained in the files named as follows:

Nominal beam width (μm)	Nominal beam length (μm)	Nominal value of distance *L* from beam's root to indenter tip (μm)	Data file name
50	50	40	50x50clminus10.txt
50	50	35	50x50clminus15.txt
50	50	30	50x50clminus20.txt
50	100	90	50x100clminus10.txt
50	100	80	50x100clminus20.txt
50	100	70	50x100clminus30.txt
20	100	90	20x100clminus10.txt
20	100	80	20x100clminus20.txt
20	100	70	20x100clminus30.txt

One way of determining Young's modulus would be to consider the data from only one force–deflection cycle. We may assume the gradient of a F–z graph to equal $3EI/L^3$ for a long narrow beam or $3EI/[(1- v^2)L^3]$ for a plate, allowing offset to be eliminated from force measurements and E to be estimated. This method is straightforward, but because the position of the nanoindenter tip relative to the end of the beam is known to within no fewer than a few micrometers, the estimate of E will itself be subject to substantial uncertainty.

A refined extraction approach is to determine the spring constant $k = F/z$ of a beam at each of the three locations where the nanoindenter tip made contact with the beam. We would then plot $k^{-1/3}$ against L, the nominal distance from the cantilever's root to the location of the nanoindenter tip. We could then assume the gradient of the ($k^{-1/3}$)–L graph to be equal to $(3EI)^{-1/3}$ for a beam or $[3EI/(1-\nu^2)]^{-1/3}$ for a plate. In this way we may be able to reduce uncertainty in the extracted value of Young's modulus. We can assume the spacing of our values of L to be known ±1 μm.

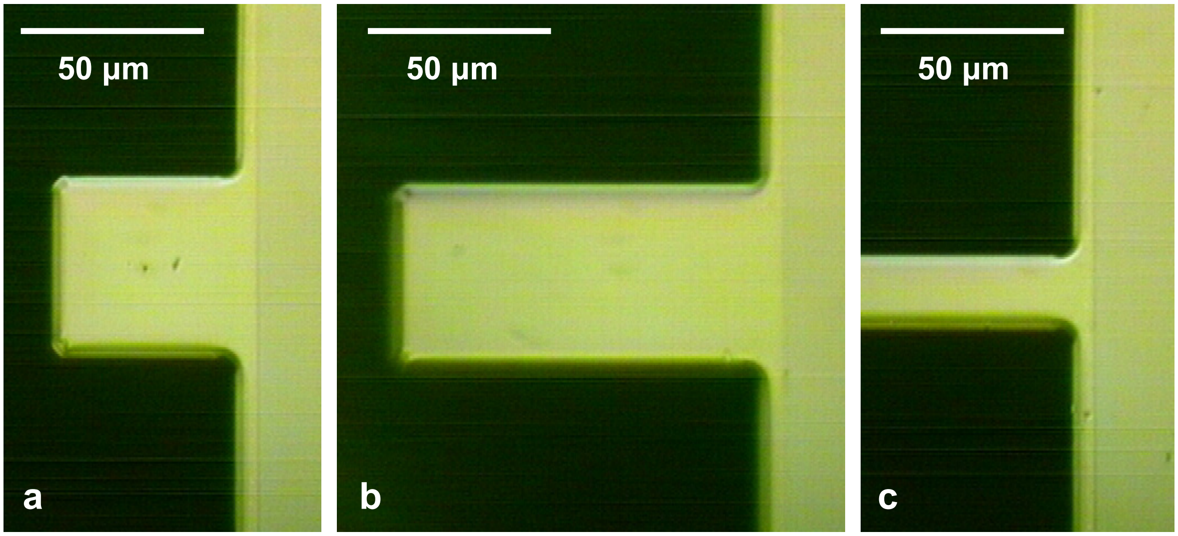


Film thickness measurement

From ellipsometry performed on a wafer after the SiN_x was deposited but before it was patterned, the film thickness was measured to be 1.015 μm, with a standard deviation of 0.516% across nine locations.

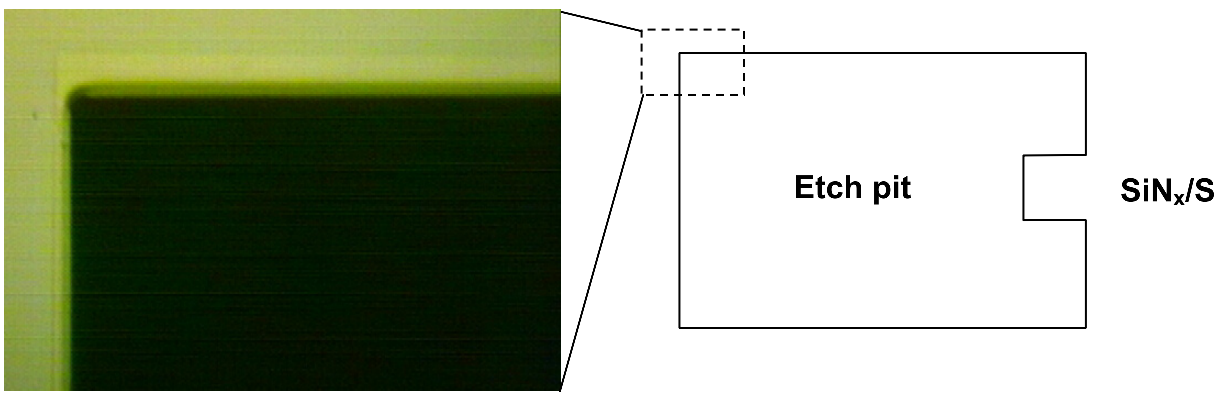
Under-cutting of the cantilevers

Below are some optical micrographs of the cantilever beams that we tested. A lighter green/yellow shade indicates silicon nitride above air; darker shading corresponds to silicon nitride on the silicon substrate.



(a) width = 50 µm, length = 50 µm
(b) width = 50 µm, length = 100 µm
(c) width = 20 µm, length = 100 µm

The etch pit was 700 µm long and 500 µm wide:



2. Extracting Young's modulus and residual stress from the deflection of fixed-fixed beams

For a fixed-fixed beam of length L, width w and thickness t, with a residual stress in the film of σ_0 and loaded with force F at its center, we have the model:

$$F = \left\{ \left(\frac{\pi^2}{2} \right) \left[\frac{\sigma_0 wt}{L} \right] + \left(\frac{\pi^4}{6} \right) \left[\frac{Ewt^3}{L^3} \right] \right\} z + \left(\frac{\pi^4}{8} \right) \left[\frac{Ewt}{L^3} \right] z^3$$

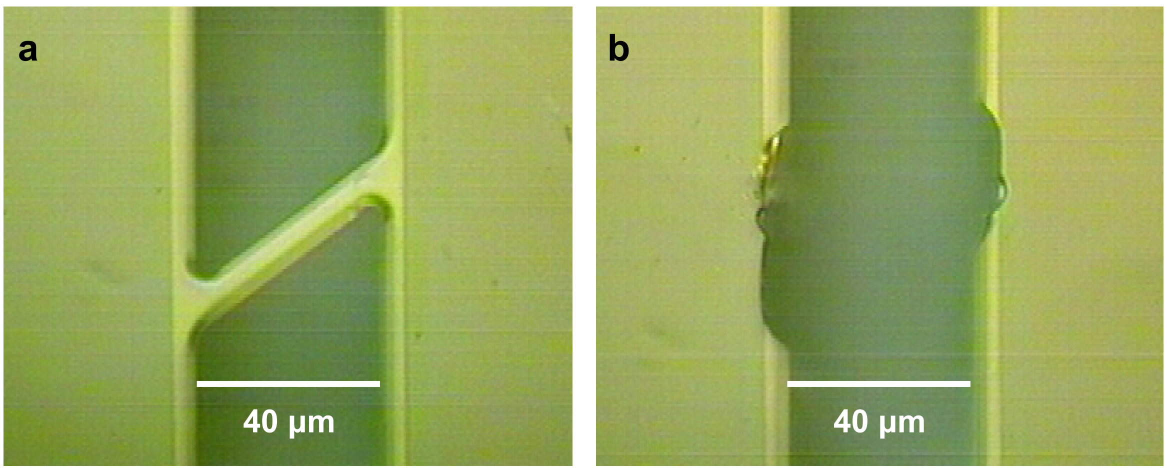
When plotting F/z against z^2, we expect data obeying this model to yield a straight line whose gradient depends on E and geometry, and whose F/z-axis intercept depends on geometry, E, and σ_0.

We deflected two fixed-fixed beams, loading them until they fractured. The force–deflection data are in the files named below:

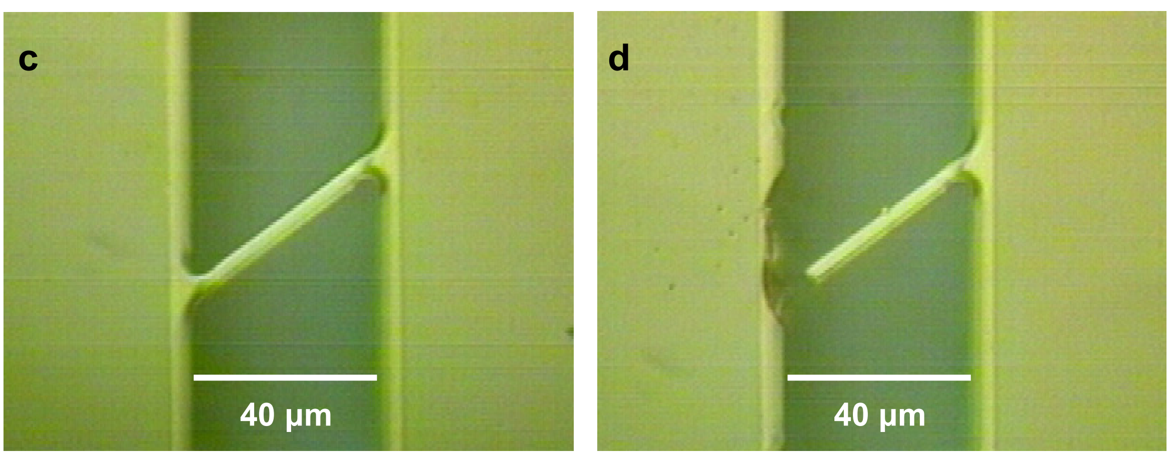
Beam length *L* (μm)	**Beam width *w* (μm)**	**Data file**
50	4	5x50ff.txt
50	8	10x50ff.txt

Note that the nominal beam ‘widths’ of 5 or 10 μm were measured parallel to the edges of the etch pits. The bridges are oriented at an angle of arctan(4/3) to the edges of the etch pits, so that the actual transverse widths of the two bridges (as they appear on the photolithographic mask) are 4 and 8 μm respectively.

Optical micrographs of the fixed-fixed beams:



8 μm-wide beam (a) before and (b) after loading



4 μm-wide beam (c) before and (d) after loading

3. Our Si-rich LPCVD SiN_x film was deposited at 775 °C. Its refractive index was measured, using ellipsometry, to be 2.52 (the measurement was made using 633 nm light). Sekimoto *et al*. [1] have experimentally related the residual stress in LPCVD silicon nitride to its refractive index. Reconcile the tensile stress that you have extracted with that predicted by Sekimoto for silicon nitride with a refractive index of 2.52.

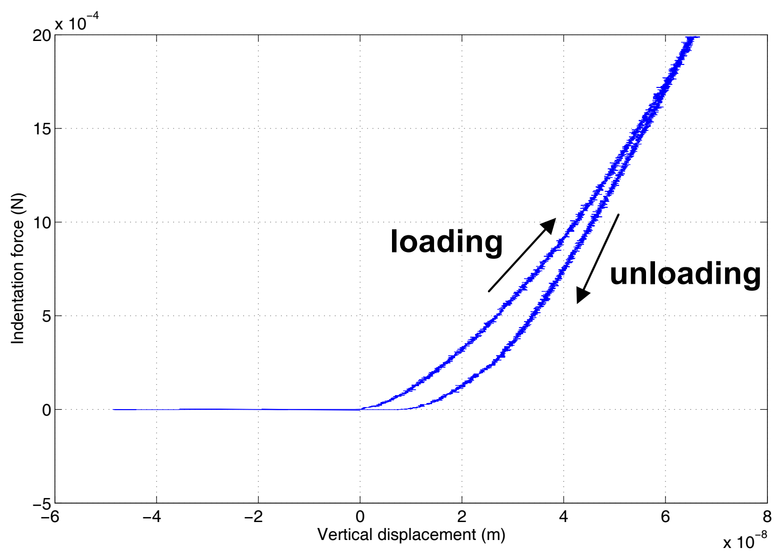
4. The literature reports an array of attempts to quantify the elastic modulus of silicon nitride; one such attempt was made by Guo *et al.* [2]. Discuss your extracted values of E in relation to that reported by Guo.

It might prove fruitful to consider these additional points:

5. A Berkovich indentation test was performed on one of our SiN_x/Si wafers after deposition but before patterning or etching. A nanoindenter tip was pressed into the film and the gradient of the force–displacement trace as the tip began to be withdrawn from the material was used to estimate the *reduced modulus* E_r, which is related to Young's modulus, E, of the material as follows:

$$\frac{1}{E_r} = \frac{(1-\nu^2)}{E} + \frac{(1-\nu_i^2)}{E_i}.$$

In this equation ν is Poisson's ratio of the SiN, E_i is Young's modulus of the diamond indenter tip (1100 GPa), and ν_i is Poisson's ratio of diamond (0.07). A typical force–displacement trace is shown below. The maximum depth of indentation was ~70 nm, approximately 7% of the SiN_x film thickness.



Force–displacement trace from Berkovich indentation test

The value of the reduced modulus, averaged over 15 locations on the film, was 173±2 GPa.

6. Another way to determine the elastic modulus of MEMS materials is to measure the resonance frequency of a structure made from the material [3]. The resonance frequency, *f*, of a cantilever beam is given by:

$$f = \frac{1}{2\pi}\sqrt{\frac{2Et^2}{3\rho L^4}}$$

where ρ is the mass density of the film, and L is the length of the beam. We measured the resonance frequency of a cantilever on one of our wafers — one with a width of 20 μm and a length of 200 μm. The sample was glued to a piezo buzzer and the buzzer was actuated with a signal containing a wide range of frequencies. A laser Doppler vibrometer was used to measure the amplitude of the resulting vibrations of the cantilever as a function of frequency. The measured first-order resonance frequency was 30.25 kHz. Using the value that you have extracted for Young's modulus, make an estimate of the film's density based on the measured resonance frequency. Is this estimate reasonable?

7. The data from the fixed-fixed beam tests show that the beams fractured during loading. Can you estimate the fracture strength of the silicon nitride film?

Further reading that might inform your discussion

Menčík [4] provides a comprehensive review of possible parasitic effects in the estimation of Young's modulus from beam bending tests. Ashwell [5] discusses in detail the origin of plate effects. McShane [6] investigates the conditions under which cantilever deflections will deviate appreciably from those predicted by the linear elastic model considered in this document. Osterberg and Senturia [7] have devised a MEMS materials testing method, 'MTest', that relies on the electrostatic deflection of beams and membranes to determine Young's modulus and residual stress.

References

[1] M. Sekimoto, H. Yoshihara and T. Ohkubo, "Silicon nitride single-layer x-ray mask," *J. Vac. Sci. Technol.,* vol. 21, pp. 1017-1021, 1982.

[2] H. Guo and A. Lal, "Die-level characterization of silicon-nitride membrane/silicon structures using resonant ultrasonic spectroscopy," *J Microelectromech Syst,* vol. 12, pp. 53, 2003.

[3] P. Neuzil, U. Sridhar and B. Ilic, "Air flow actuation of micromechanical oscillators," *Appl. Phys. Lett.,* vol. 79, pp. 138-140, 2001.

[4] J. Mencik and E. Quandt, "Determination of elastic modulus of thin films and small specimens using bending metods," *J. Mater. Res.,* vol. 14, pp. 2152-2161, 1999.

[5] D. G. Ashwell, "The anticlastic curvature of rectangular beams and plates," *J. R. Aeronaut. Soc.,* vol. 54, pp. 708-715, 1950.

[6] G. J. McShane, M. Boutchich, A. S. Phani, D. F. Moore and T. J. Lu, "Young's modulus measurement of thin-film materials using micro-cantilevers," *J Micromech Microengineering,* vol. 16, pp. 1926-1934, 2006.

[7] P. M. Osterberg and S. D. Senturia, "M-TEST: A test chip for MEMS material property measurement using electrostatically actuated test structures," *J Microelectromech Syst,* vol. 6, pp. 107, 1997.