Measurement of Young's modulus via mechanical test of MEMS cantilevers

Tony Hyun Kim
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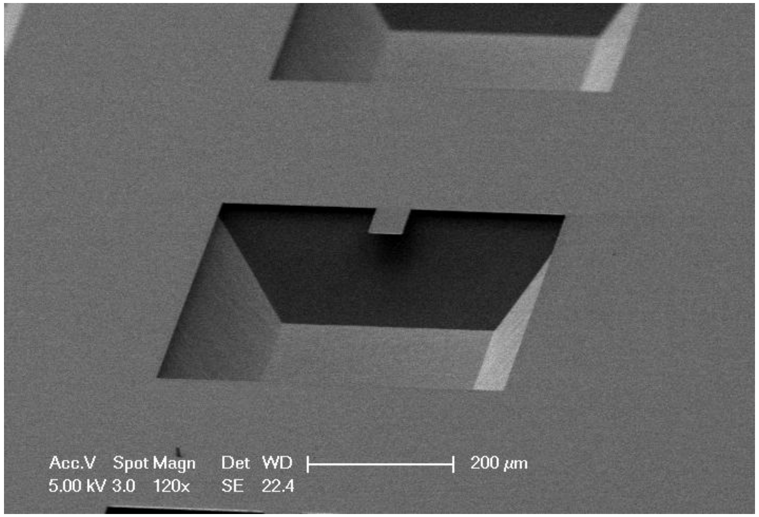
6.152: MEMS Presentation

Topics to be discussed

1. Introduction
    1. MEMS Cantilevers, Fixed-fixed beams
    2. Theory of cantilever mechanics: Young's modulus, etc.
2. Fabrication details
3. Experimental setup for mechanical test
4. Analysis and results
    1. Young's modulus of SiNx
    2. Breaking point of the fixed-fixed beam
5. Sources of error
6. Conclusions

MEMS Cantilevers and Fixed-fixed beams

- Most ubiquitous structure in MEMS
- Starting point for many applications:
  - Sensors
  - Platform for material experiments
- It's easy to build and easy to use (in principle).



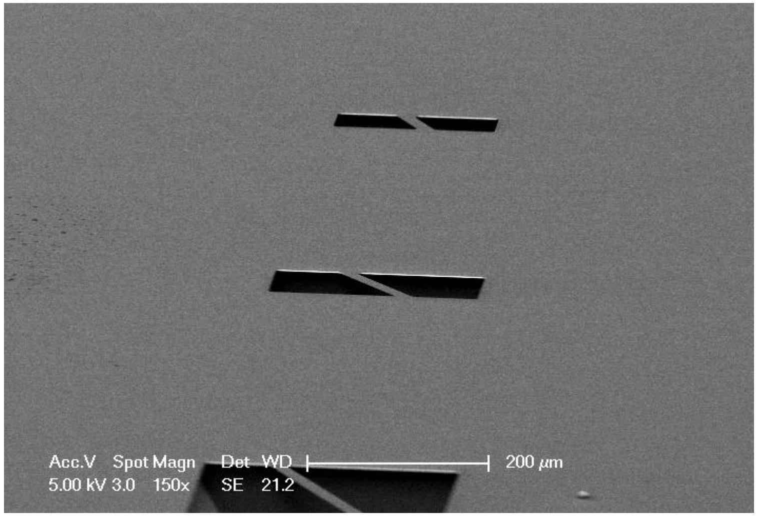


Image source: Hayden, Taylor. "MEMS Analysis 2" (On 6.152 Stellar)

MEMS Cantilevers and Fixed-fixed beams

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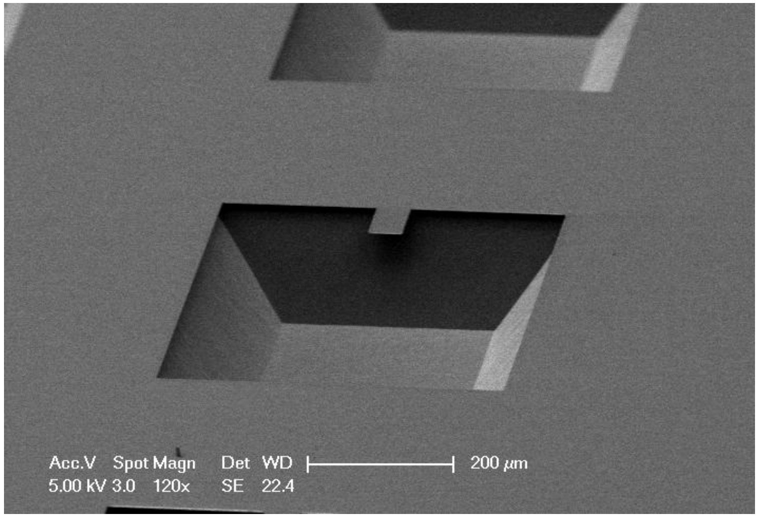
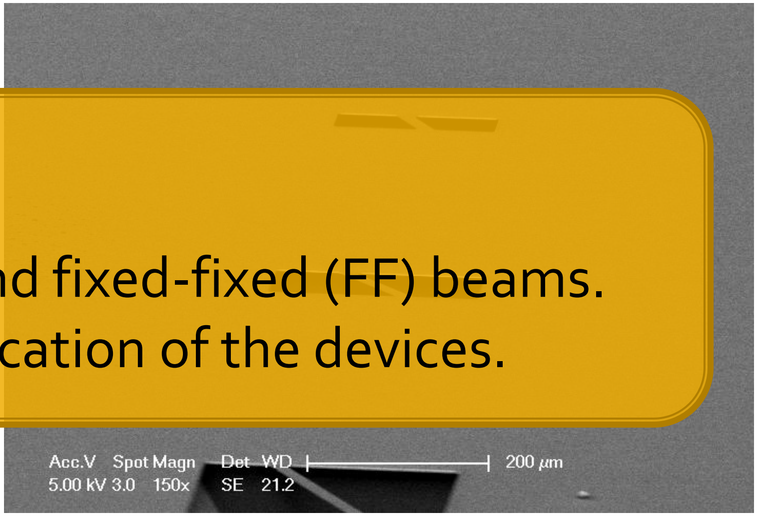
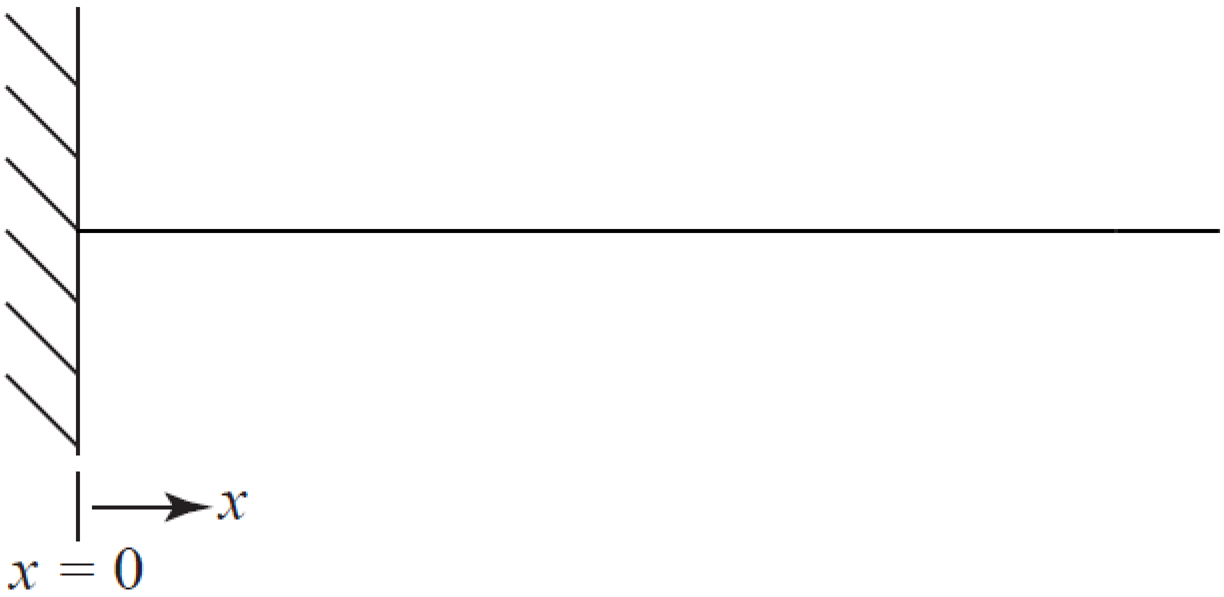


Our experimental goals:

•Build an array of MEMS cantilevers and fixed-fixed (FF) beams.
•Perform optical and mechanical verification of the devices.



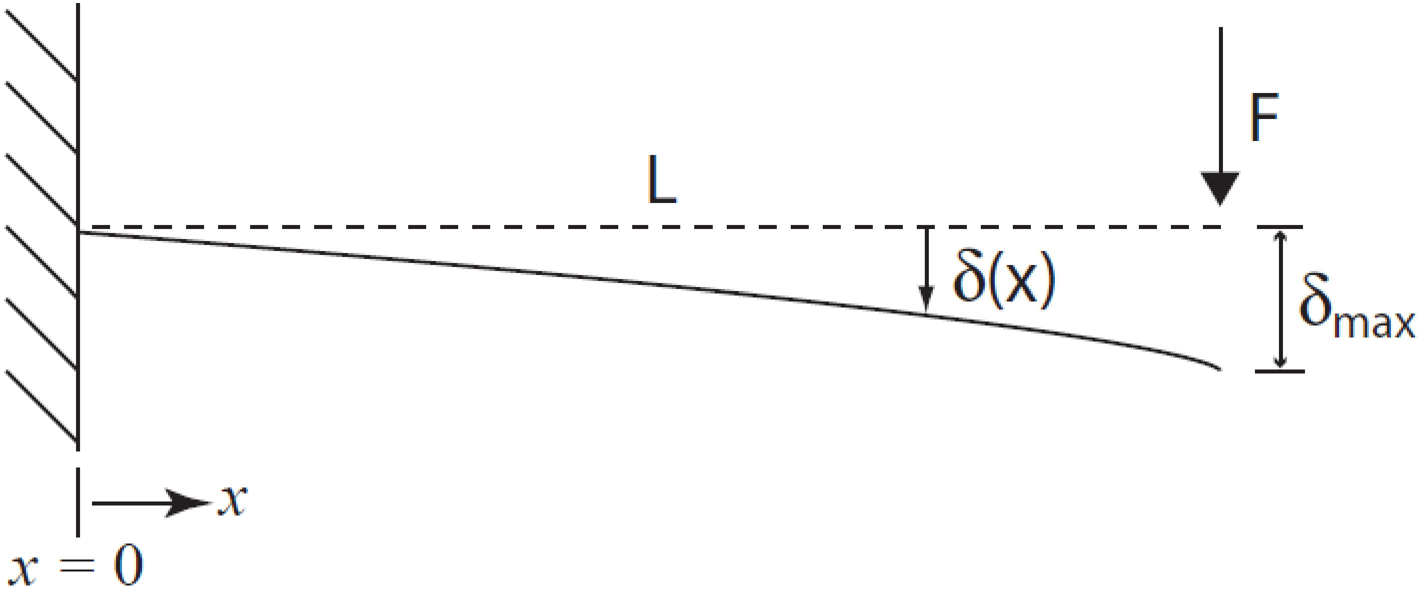
Theory of cantilever mechanics



- Once the structure is built, we want to test it.
  - i.e. perform **consistency checks** against literature

Image source: Schwartzman, Alan. "MEMS Analysis 1" (On 6.152 Stellar)

Theory of cantilever mechanics

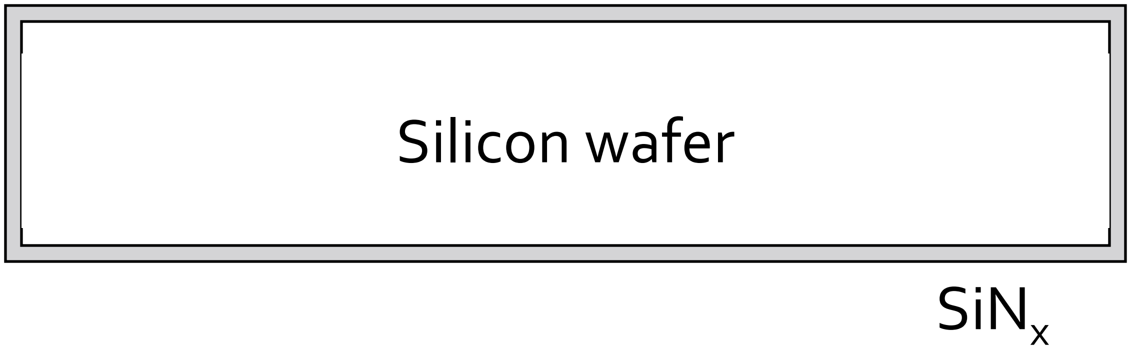


- The deflection of the target point (at distance L from fixed end):

$$F / \delta_{max} = k = \frac{1}{4} \cdot \frac{Wt^3}{L^3} \cdot E$$

- Young's modulus (E) is a **material property** measuring stiffness.

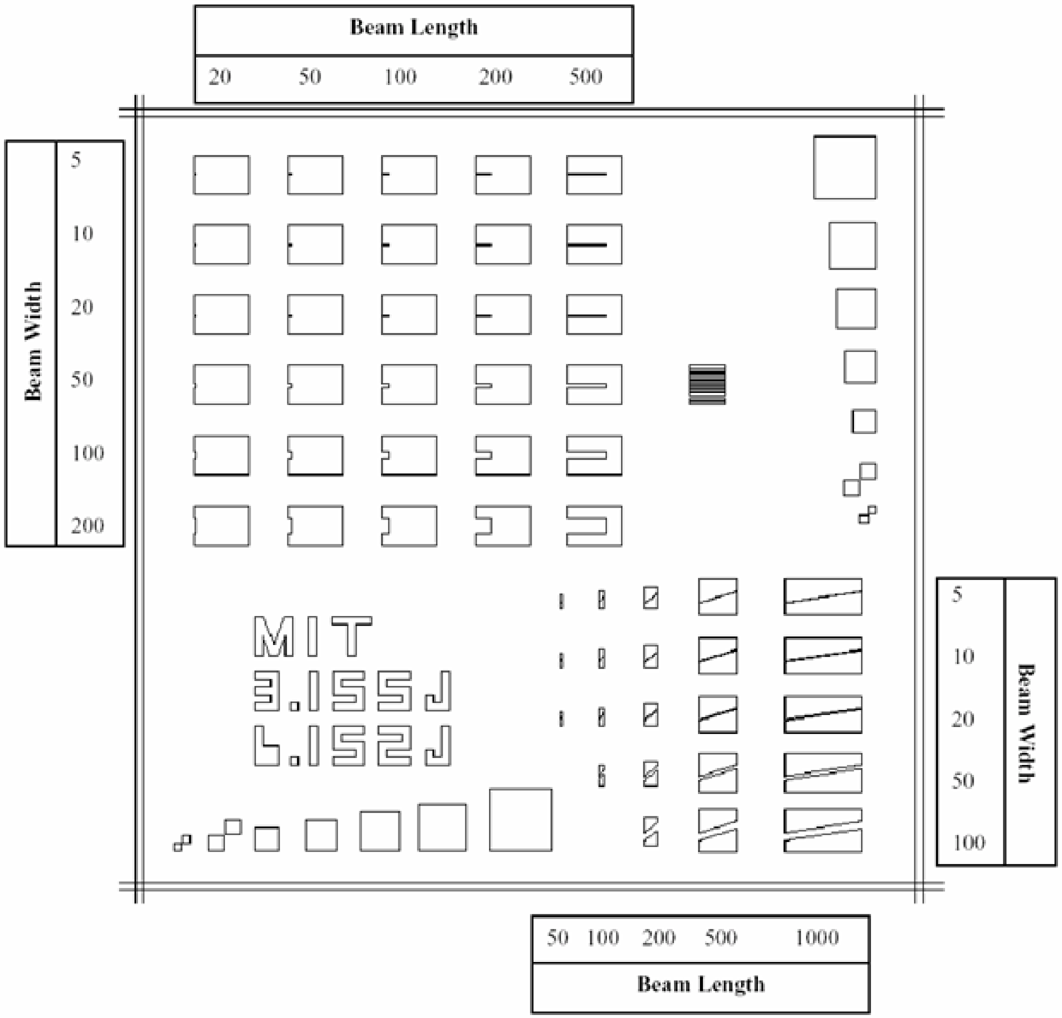
Fabrication details (1)



- Silicon nitride was deposited on wafer by Scott.
- Thickness was measured by ellipsometry:

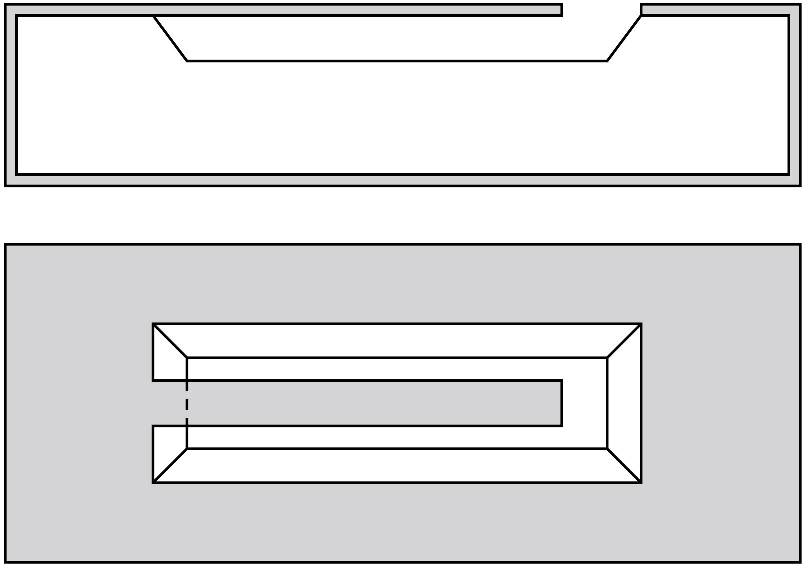
$$t = (1.94 \pm .01)\ \mu m$$

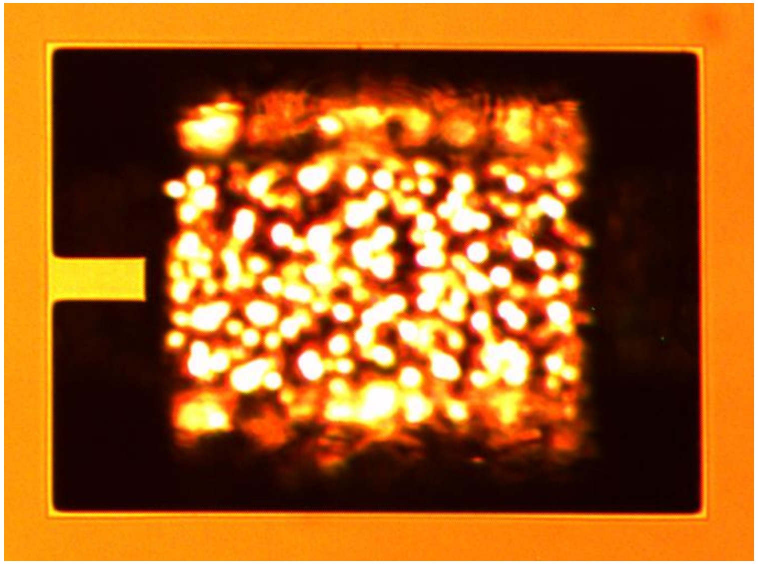
Fabrication details (2)



- Silicon nitride patterned according to mask on left.
- Pattern transferred by contact lithography.
- The nitride was etched by SF_6/plasma.

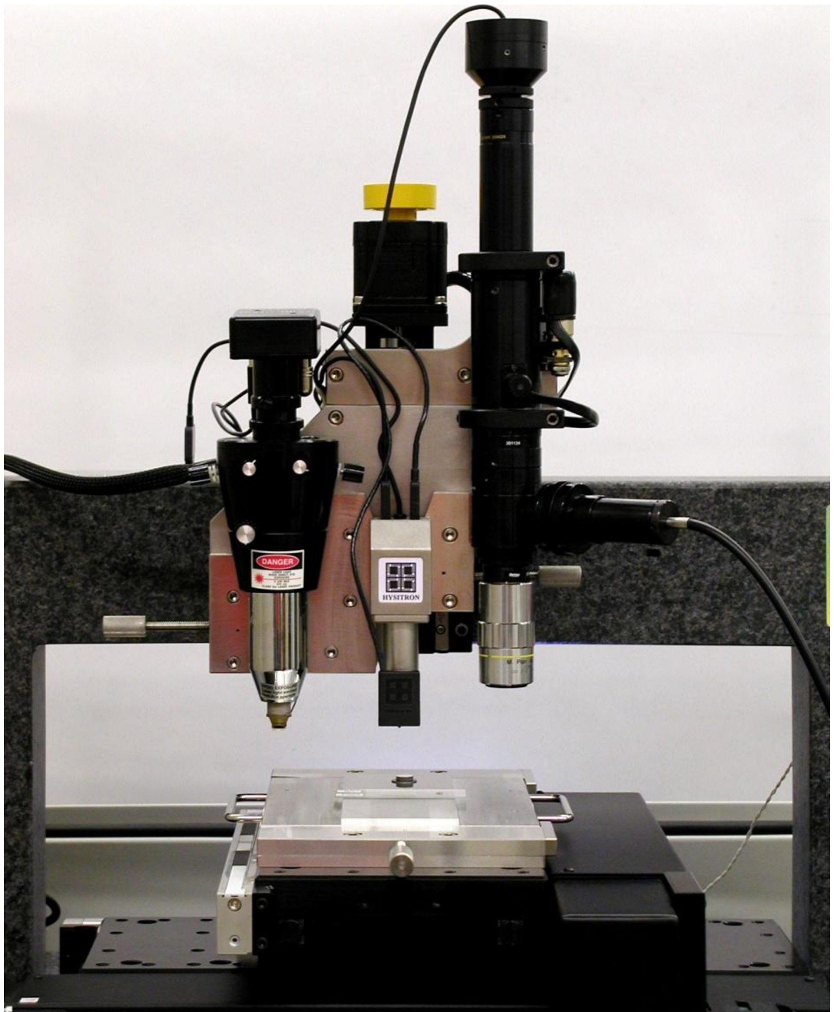
Fabrication details (3)



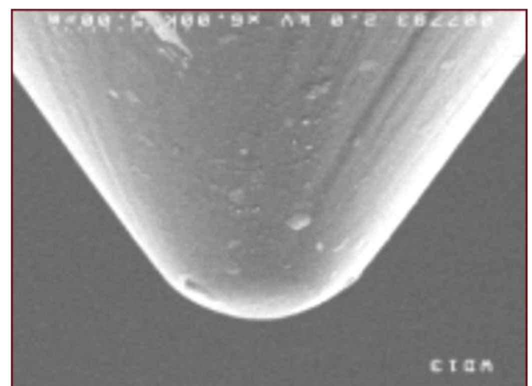


- Finally, an anisotropic etch (KOH) was utilized to etch the Si bulk.
  - Two hour etch in 80ºC KOH bath.
- The <111> orientation is stable against KOH →
  - Allows for the material below the bridge to be removed first.

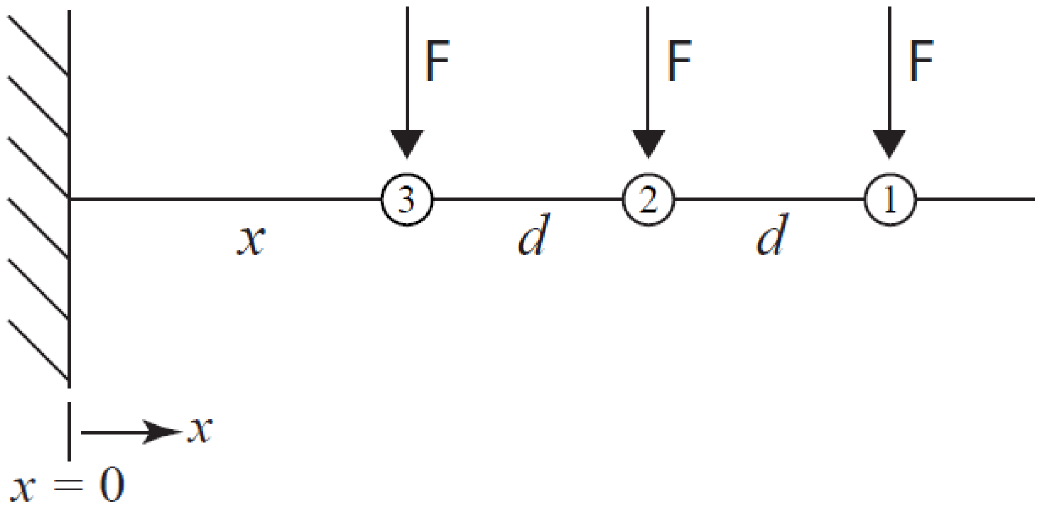
Experimental Setup: Mechanical test



- “TriboIndenter” in the NanoLab
- Optical microscope:
  - Position target.
- Force-displacement transducer:
  - With a blunt tip.



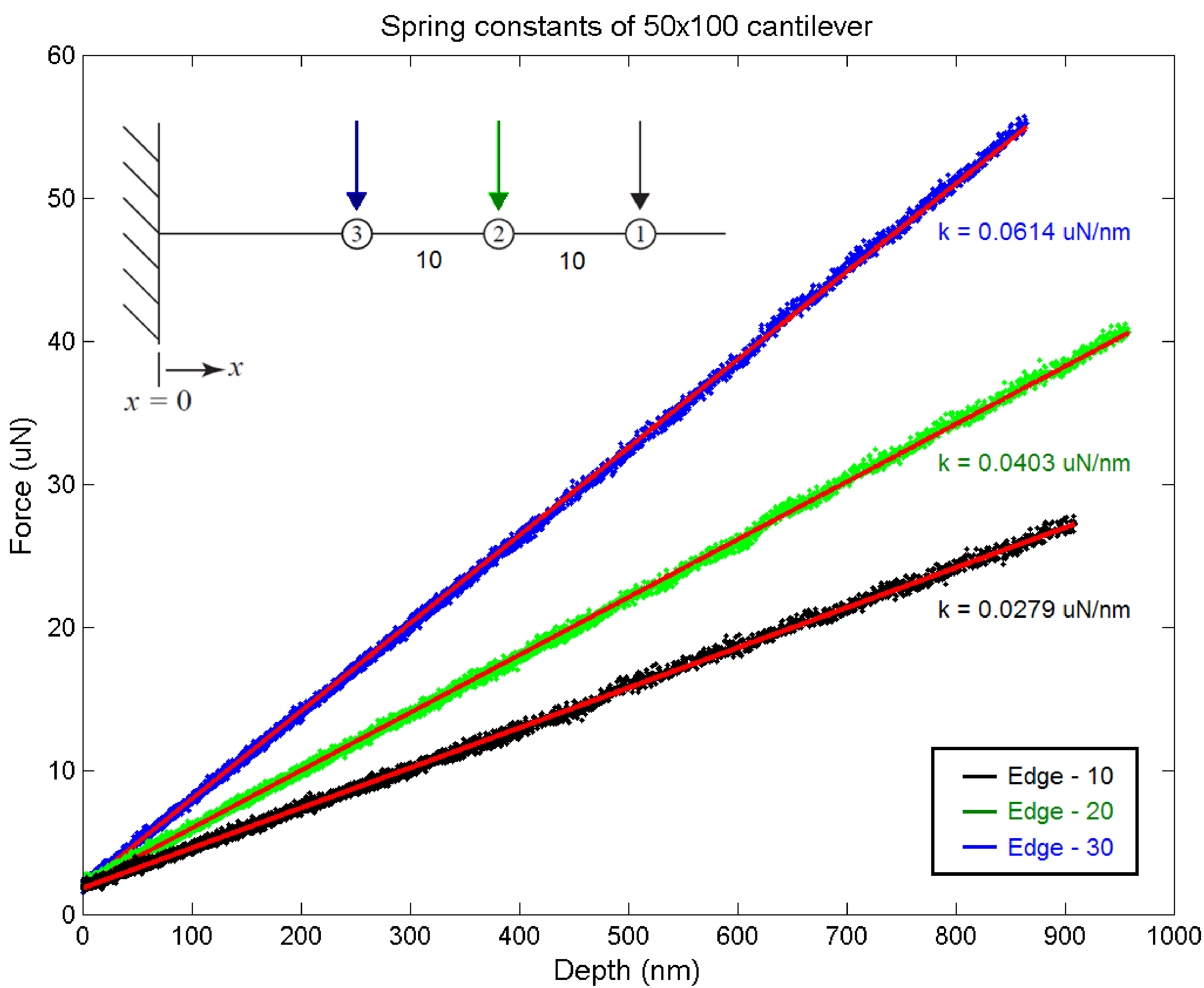
Experimental Setup: Mechanical test



- The spring constant is dependent on the point of application of force, L:

$$F/\delta_{\max} = k = \frac{1}{4} \cdot \frac{Wt^3}{L^3} \cdot E$$

- Can deduce Young's modulus without L, by the above scheme



Spring constants of 50x100 cantilever
3
2
1
10
10
x
x = 0
k = 0.0614 uN/nm
k = 0.0403 uN/nm
k = 0.0279 uN/nm
Edge - 10
Edge - 20
Edge - 30
Force (uN)
Depth (nm)
0
10
20
30
40
50
60
0
100
200
300
400
500
600
700
800
900
1000

Results: Young's modulus

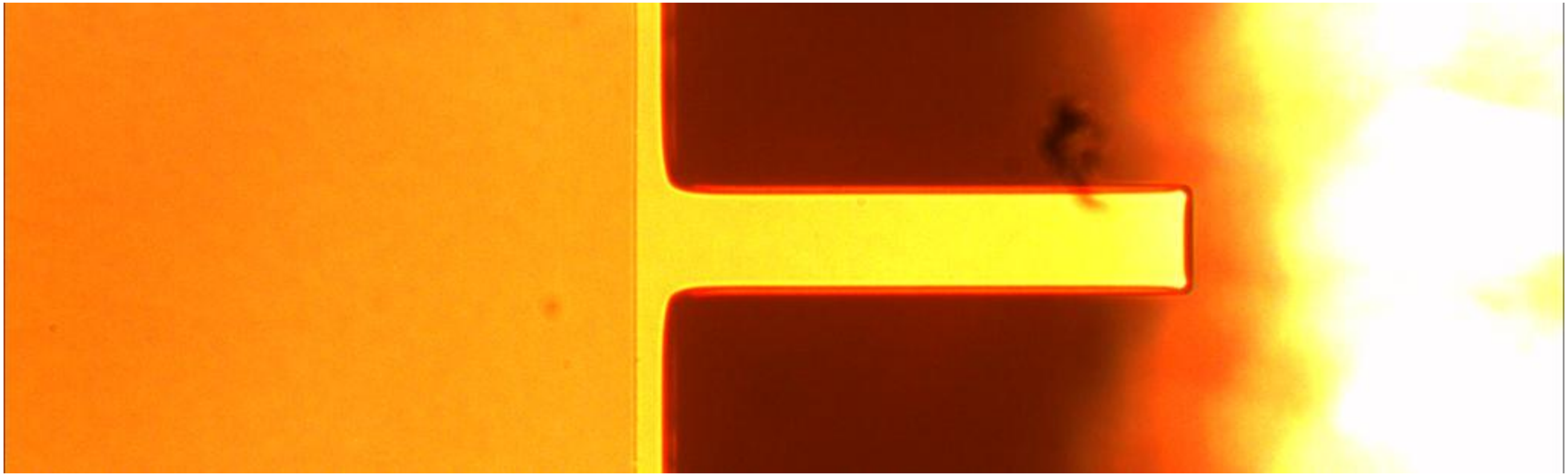
- The Young's modulus was computed using the following: $E = \frac{4}{b^3 W t^3}$
  - "b" is the slope of $k^{-1/3}$ vs. L
  - Optically measured width (W); thickness (t) from ellipsometry

TABLE I: Results of the Young's modulus experiment

Source	Value (GPa)
20x100 Cantilever	180
50x100 Cantilever	186
Average	183 ± 4
Literature (Guo, Lal 2003)	195 ± 9

- Our results are within 1 std. of published values.

Sources of error in Young's modulus determination



- Geometric complications
  - Sloped cantilevers → "Effective" width smaller
  - Undercut below the fixed-end

$$E = \frac{4}{b^3 W t^3}$$

Conclusions

- Constructed MEMS cantilevers (and fixed beams)
- Performed a mechanical experiment using the cantilevers
  - Provides consistency check:

$$E_{meas} = (183 \pm 3)\ GPa$$

$$E_{lit} = (195 \pm 9)\ GPa$$

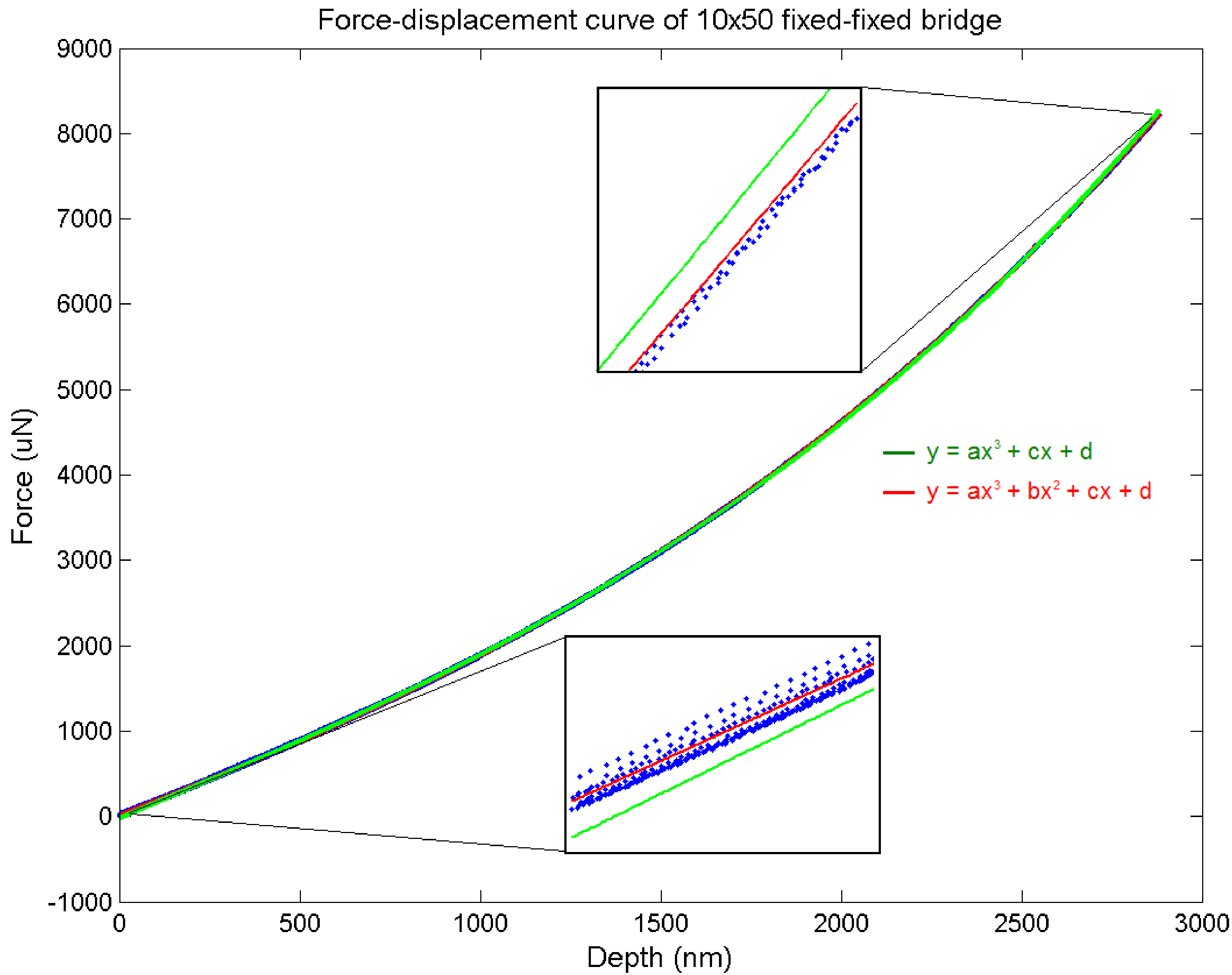
  - Also verifies MEMS as useful platform for doing material studies.

Fixed-fixed beam analysis

- Model is:

$$F = \left\{ \frac{\pi^2}{2} \cdot \frac{\sigma_0 W t}{L} + \frac{\pi^4}{6} \cdot \frac{E W t^3}{L^3} \right\} \cdot \delta + \left\{ \frac{\pi^4}{8} \cdot \frac{E W t}{L^3} \right\} \cdot \delta^3$$

- Young's modulus is directly related to the cubic coefficient.


Force-displacement curve of 10x50 fixed-fixed bridge
Force (uN)
Depth (nm)
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
-1000
0
500
1000
1500
2000
2500
3000
y = ax3 + cx + d
y = ax3 + bx2 + cx + d

Fixed-fixed beam analysis

- Young's modulus through the cubic coefficient a:

TABLE I: Fixed-fixed beam analysis

Method	Cubic coeff. ($\mu N/nm^3$)	Young's modulus (GPa)
$ax^3 + bx^2 + cx + d$	1.02×10^{-7}	79
$ax^3 + cx + d$	1.31×10^{-7}	103
Literature (Guo, Lal 2003)	N/A	195 ± 9

- Significant deviation from published values.

Fixed-fixed beam analysis

- Possible sources of errors to consider: $$E = \frac{8}{\pi^4} \cdot \frac{L^3}{Wt} \cdot a$$
  - Sloped edges have huge effect on width: 6 vs. 9 um.
  - Bridge is slanted
- Force-displacement profile prefers quadratic term.