KOÇ UNIVERSITY
COLLEGE OF ENGINEERING

MECH 525
Mechanics of Microsensors

Project no: #1
Project title:
FORCE MEASUREMENT IN mN RANGE

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Objective

Residual stress plays a critical role in the performance and reliability of microelectromechanical systems (MEMS). These devices, which integrate mechanical and electrical components on a miniature scale, are subject to complex stress fields that arise during fabrication and operation. Residual stress can cause deformation, warping, cracking, and other types of mechanical failure, which can significantly impact the functionality and lifespan of MEMS devices. However, residual stress can also be intentionally engineered to achieve desirable mechanical properties and improve device performance. For example, residual stress can be used to enhance the sensitivity and accuracy of MEMS sensors, or to control the actuation and deformation of MEMS structures. Therefore, understanding and controlling residual stress is crucial for the design, fabrication, and optimization of MEMS devices. This project aims to investigate measurement of residual stress using a passive strain measurement

Methodology

The proposed strain sensor is shown in Figure 1. After etching a sacrificial layer, tensile or compressive residual strains in the test beam are amplified due to the rotation of the slope beam. The displacement of the Vernier gauge is measured under the optical microscope.

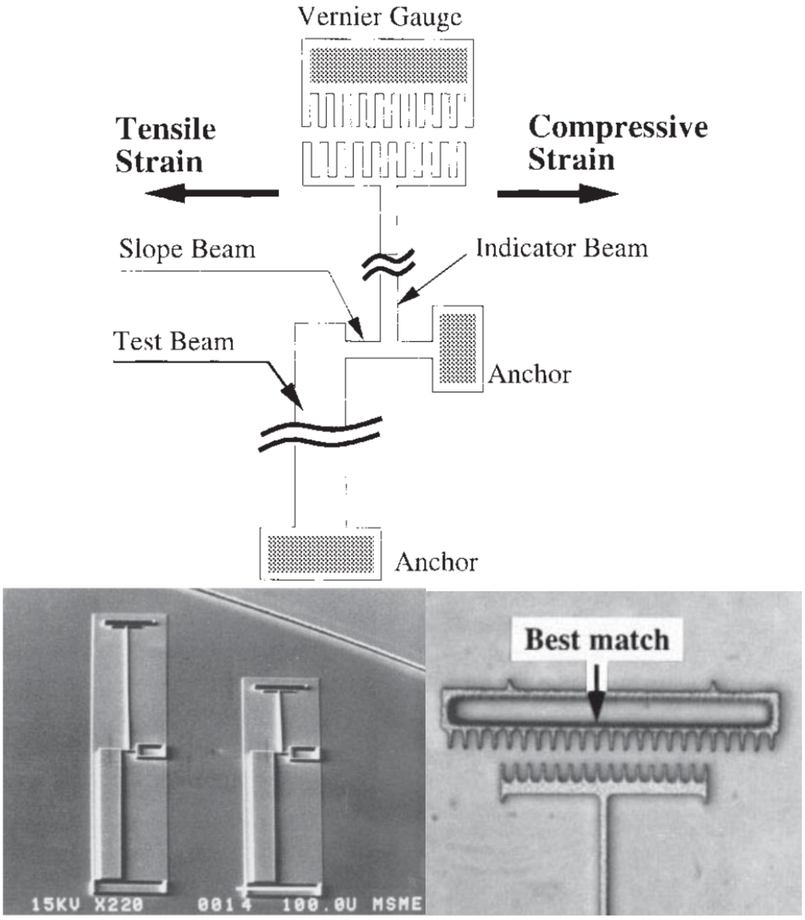


Figure 1 sensor design Lin et al [1]

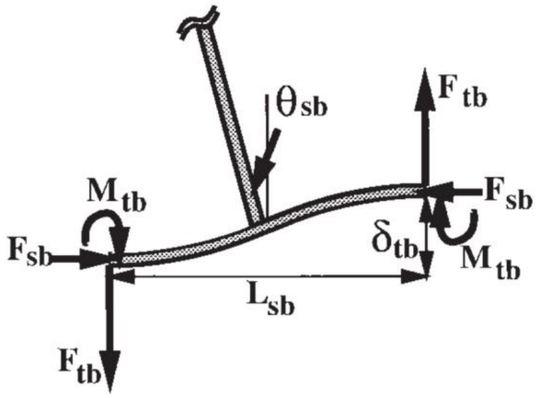


Figure 2 sensor working mechanism [1]

The equations that describe the mechanics of the sensor are shown below.

$$\Theta_{sb} \sim \tan(\Theta_{sb}) = \frac{3\delta_{tb}C}{2L_{sb}}$$

$$C = \frac{1-d^2}{1-d^3}$$

$$\sum M_A = 0$$

$$M_1 + M_2 - FL = 0$$

$$\sum M_B = 0$$

$$M_2 - M_1 - FL = 0$$

$$M_1 + M_2 = FL$$

$$M_1 = M_2 = \frac{FL}{2}$$

$$\frac{d^2w}{dz^2} = -\frac{1}{EI}M_x(z) = (\frac{FL}{2} - FZ)\frac{1}{EI}$$

$$\frac{dw}{dz} = \left(\frac{FL}{2}Z - \frac{F}{2}Z^2\right)\frac{1}{EI} + G1\frac{1}{EI}$$

Stiffness of the slope beam is given by

$$K = \frac{F}{W(z=L)} = \frac{12\ EI}{L^3}$$

$$\varepsilon = \frac{2\ L_{sb}\delta_v}{3L_{ib}L_{tb}}$$

Assuming uniform residual stress throughout the cross section of the beam and using Hooke's law

$$\sigma_{res} = E\varepsilon_{res} = E\frac{2\ L_{sb}\delta_v}{3L_{ib}L_{tb}}$$

Which gives the sensitivity as

$$S = \frac{\delta_v}{\sigma_{res}} = \frac{3}{2}\frac{L_{ib}L_{tb}}{EL_{sb}} \quad [\frac{\mu m}{MPa}]$$

Table 1 parameters values

Dimensions (μm)	S= 0.1 μm/MPa	S= 5 nm/MPa	S= 1.7 μm/MPa
L_{tb}	453	113	982
L_{sb}	20	20	5.1
L_{ib}	500	100	1000
W_{tb}	30	10	10
W_{sb}	1.2	1.2	0.5
W_{ib}	2	2	2
h	4	4	4

Residual stress slope beam

$$\frac{M_{sb}}{M_{tb}} = \frac{\varepsilon\, \omega_{tb}^3\, L_{sb}^3}{4L_{tb}^3 \omega_{sb}^3} \ll 1$$

Stiffness of the slope beam

$$\frac{k_{sb,tb}}{k_{tb,tb}} = \frac{L_{tb}\, \omega_{sb}^3}{L_{sb}^3\, \omega_{tb}} \ll 1$$

Buckling in the test beam

$$\varepsilon_{max,com} \leq \frac{\pi^2 h^2 \omega_{tb}\, L_{sb}^3}{3\omega_{sb}^3\, L_{tb}^3}$$

Table 2 Analysis & Modeling

	residual stress slope beam <<1	stiffness of the slope beam <<1	$\varepsilon_{max,\,com}$ (buckling in the test beam)	magnification
paper	0.00035	0.0036	1.46 %	37.16
High sensitivity	0.00047	0.0032	7.86 %	37.16
low sensitivity	0.00112	0.0024	168.89 %	7.43
Max sensitivity	0	0.092	0.059 %	264.85

Table 3 Paper model parameters [1]

Symbol	Element	value
L_{tb}	Length of the test beam	500 μm
L_{sb}	Length of the slope beam	20 μm
L_{ib}	Length of the indicator beam	500 μm
ω_{tb}	Width of the test beam	30 μm
ω_{sb}	Width of the slope beam	1.2 μm
ω_{ib}	Width of the indicator beam	2 μm
h	thickness of the thin film	2 μm
ω_v	Width of the test beam	1 μm
L_v	Length of the test beam	4 μm
	Center-to-center distance of the vernier fingers	3 μm
	Gap between top and bottom vernier fingers	2 μm

Results:
A mesh size of extremely fine was chosen with an average element quality of 0.78, which is considered good for this application. The material chosen for this project was single-crystal anisotropic silicon.

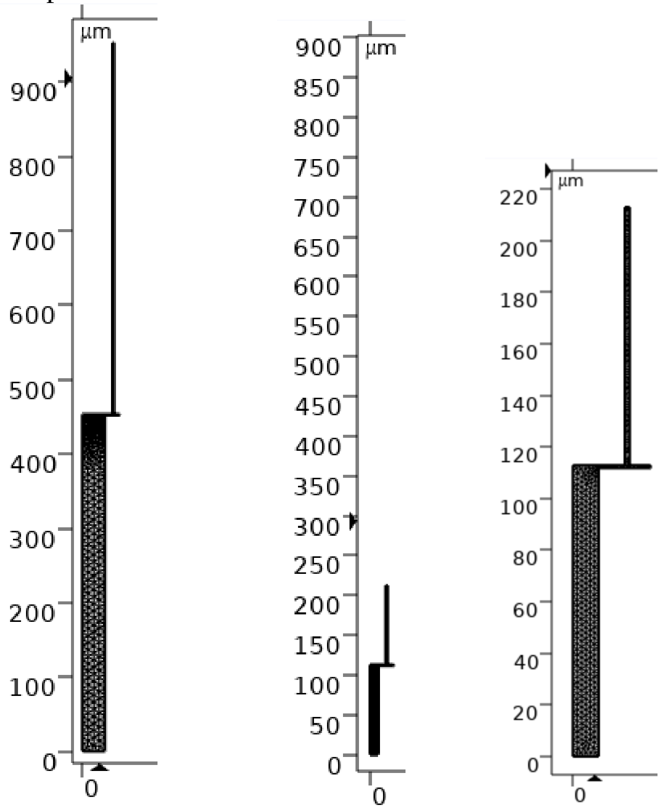


Figure 3 Mesh & Geometry of the models
(left) high sensitivity model, (middle) low sensitivity model, (right) low sensitivity model zoomed in

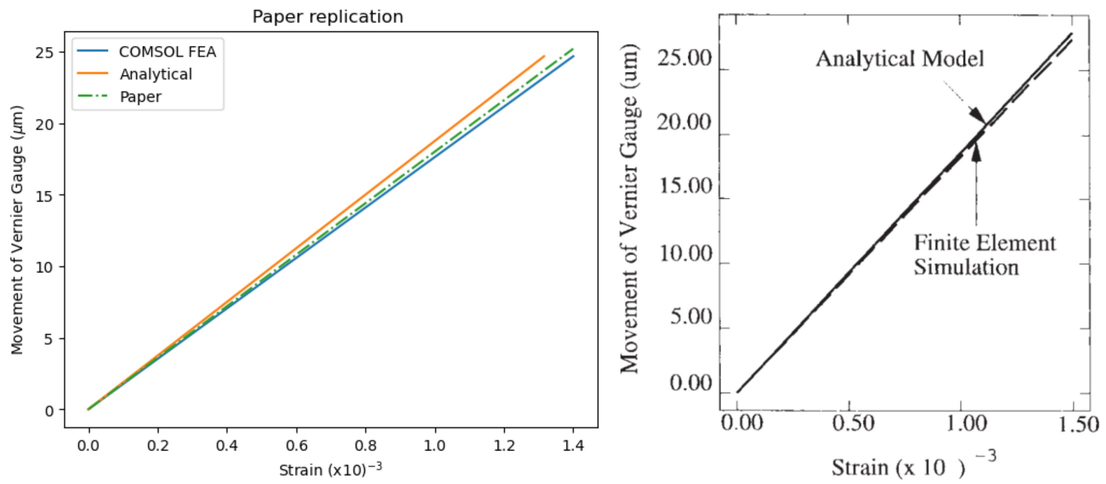


Figure 4 Replication of the paper (left), original paper graph (right)[1]

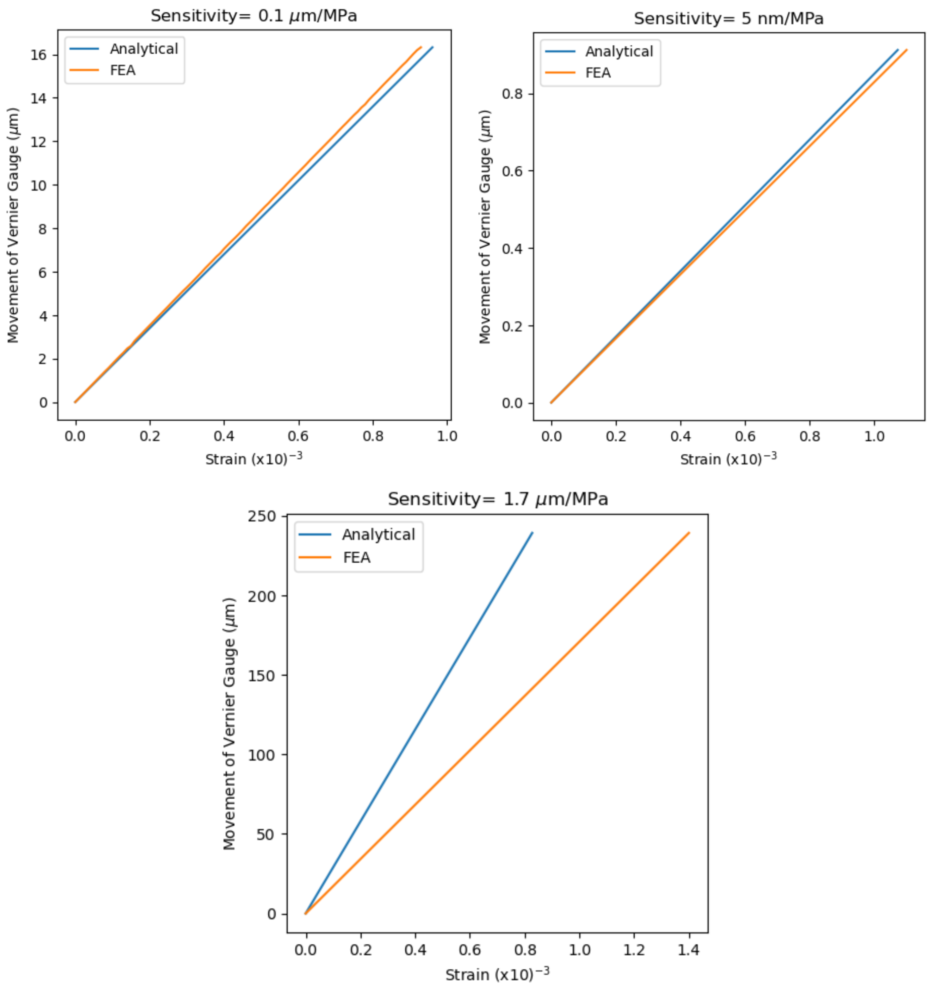


Figure 5 displacement for multiple sensitivities

The graph below shows the deflection of the slop beam (here the test beam would be released and cause the deflection due to residual stress)

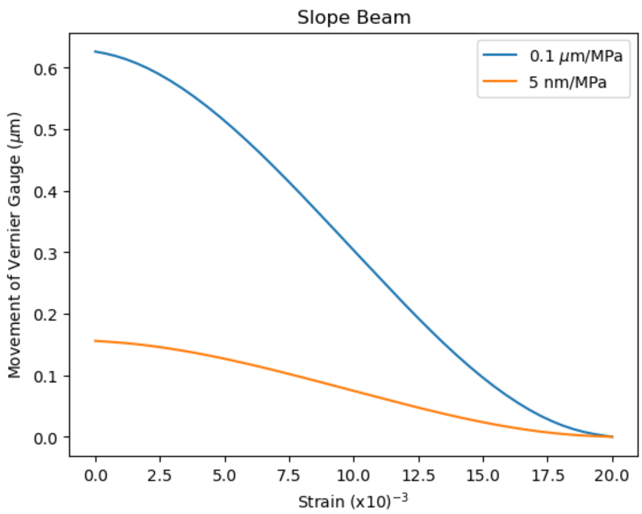


Figure 6 Slope beam deflection

Rotation [100] vs [110]:

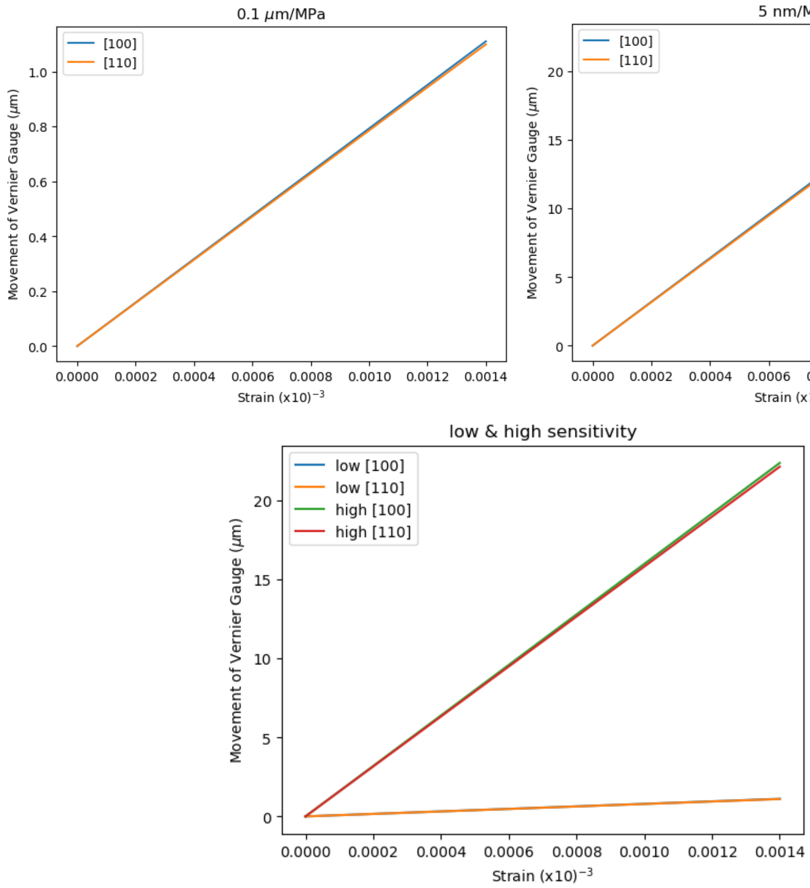
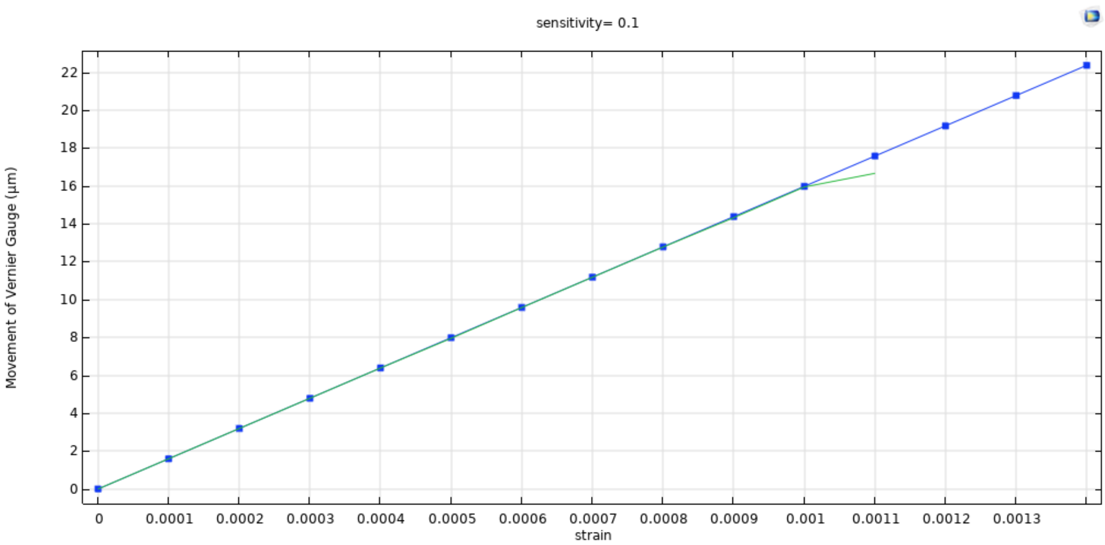


Figure 7 material rotation comparison



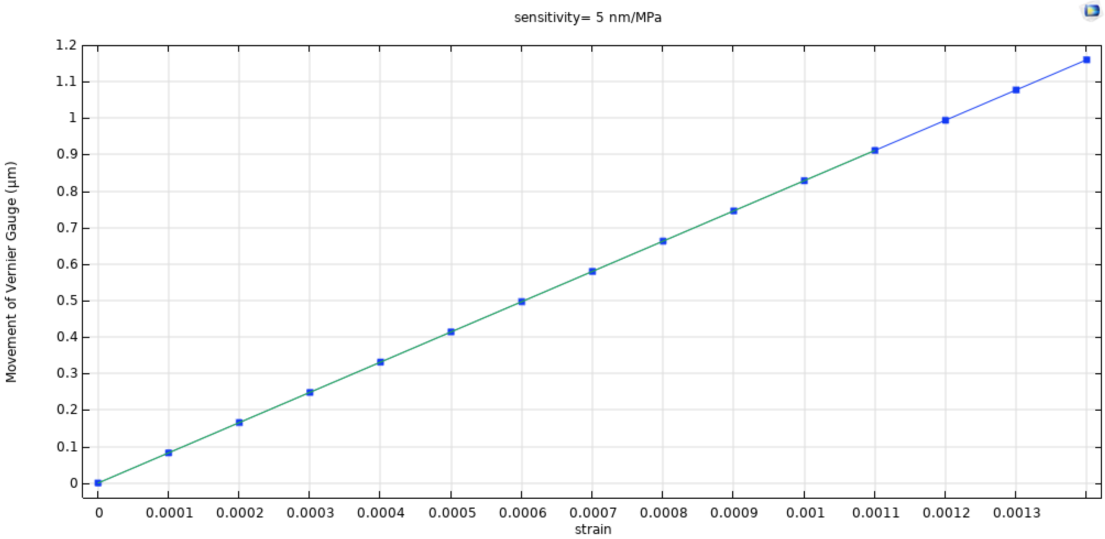


Figure 8 Linear vs Nonlinear Geometry COMSOL

Assumption for linearity is that the deflection of the beam is much smaller than the height of the beam.

Linearity is an important characteristic of sensors, including strain sensors. It refers to the ability of the sensor to provide a linear relationship between the input (stress or strain) and the output (displacement) over a certain range of values. In other words, a linear sensor produces a constant change in output signal for a constant change in input stress or strain.

The conditions for a linear Δx vs. stress (or strain) relation are as follows:

- The material of the sensor must have a linear stress-strain relationship over the range of interest. This means that the material must obey Hooke's Law, which states that stress is proportional to strain.
- The geometry of the sensor must be such that the stress or strain is uniform and does not vary significantly across the sensor.
- The bonding between the sensor and the object being measured must be uniform and not vary significantly across the sensor.
- The sensor must have a linear response over the range of stress or strain being measured.

To ensure the minimum acceptable limit for linearity, certain geometrical conditions can be followed. For example, the sensor should have a uniform cross-section and the length-to-diameter ratio should be at least 10:1. The sensor should also have a small aspect ratio (thickness-to-width ratio), as this reduces bending and ensures a more uniform stress distribution. Additionally, the sensor should be bonded uniformly and securely to the object being measured, with minimal adhesive thickness and no air gaps between the sensor and the object. By following these geometrical conditions, the strain sensor can ensure a minimum acceptable limit for linearity, which is crucial for accurate and reliable measurement of stress and strain.

Discussion/Comparison with Literature

When looking at the paper replication results Fig. 4, we see that the graph matches the paper to a good amount. This shows that both the analytical and FEA approach are valid with comparison to published work in the literature (error= 2.14 %).

For the 2 sensors that I am asked to design, I tried to follow the parameter requirements and showed the parameter I chose in Table. 1 and the result of the sensor measurements in Fig. 5. As shown, the values of low and high sensitivities are close to the analytical values and with very good match at small strain values and minor deviation at higher strain values .
The reason we see discrepancy between analytical and FEA values for larger displacements, is simply because of the linearity assumption. This assumption will only hold for small Θ values / small displacement. Thus, the analytical results for the high sensitivity sensor are expected to deviate from FEA, and this is what we see. Sensitivity values are shown in Table. 1 and Table. 2. For extremely high sensitivity, the assumptions made simply don't hold, and we see significant deviation between analytical and FEA results, and we will reach the buckled region when we apply high strain (like is shown in Figure 5).

The change in the orientation of [100] to [110] didn't result in significant change as we can see from the FEA results. This can be attributed to the way the sensor works since we don't have normal stress applied, which means that changing the silicone orientation for our application will not result in huge difference.

According to He et al [4], stress values of 132-163 MPa are common in practical applications. The table below provides a comparison of multiple sensors all of which measure displacement [4]. The resolution varies among the sensors, and some have low resolution (displacement of only 0.3 μm) and some of high resolution (displacement of 13.2 μm which was done by same sensor of Lin et al) [4].

Table 4 literature comparison [4]

Test results and comparison of each stress test method

Stress test method	Measured displacement (μm)	Calculated stress (MPa)	FEA stress (MPa)	Res.	Comment
Micro bridge (PolySi)	0.5	− 163	–	Low	Only for compressive stress, needs test array
Diamond structure (PolySi)	0.3	–	− 126	Low	The structure size is not big enough; the buckled deflection is very small
Double indicator structure (PolySi)	12.5	− 137	− 143	Norm.	Good method
Folded indicator structure (PolySi)	10.8	− 132	− 140	Norm.	Good method
Micro strain gauge (PolySi)	13.2	− 145	− 149	High	The best method
Long–short beam strain sensor (PolySi)	5.3	− 151	− 157	High	Quite good method
Ring structure (SiN)	0.4	–	+ 250	Low	The buckled value is very small

− indicates the compressive stress for polysilicon. + indicates the tensile stress for silicon rich nitride.
Res. indicates the resolution of the measurement.

As we observe from the table, common measured displacement ranges from 0.3 μm to13.2 μm. The values I got by following the work of Lin et al gave me up to 25 μm for a strain of near 0.0015, which is comparable to other works.
Another good sensor design is the Long-Short beam strain sensor designed by Pan and Hsu [3] and shown in Figure. 9 below.

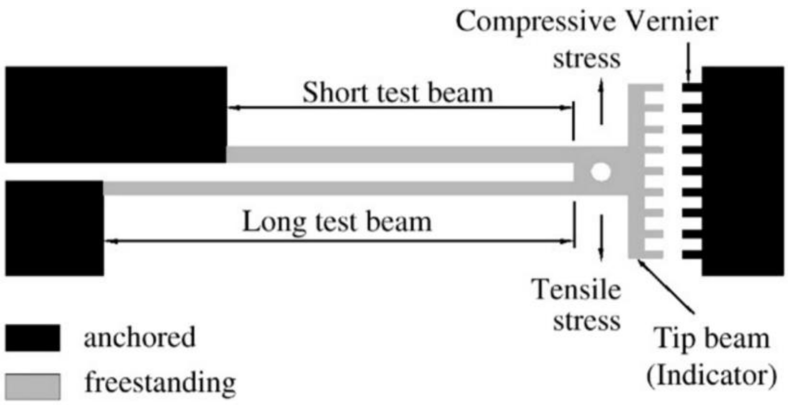


Figure 9 long-short beam strain sensor [4]

The microstructure of this sensor is composed of two cantilever beams of different lengths joined by a short tip beam [4]. The purpose of the two cantilever beams is to serve as test beams while the tip beam functions as an indicator [4]. The difference in elongation or contraction of the two test beams due to changes in temperature leads to deflection of the beams and amplifies the lateral displacement of the tip. The two beams are connected by a tip beam as an indicator [4]. After the freestanding part is released, the two test beams will extend or contract due to residual stress in the thin film. The displacement (δ) caused by the deflection of two test beams can be read out using indicator and vernier by optical microscope or SEM [4]. This sensor has a similar working mechanism to the one we worked on (Micro strain gauge by Lin et al), but reported lower displacement measurements for higher stress values.

To fabricate the device, microstructures made of polycrystalline silicon films produced via low-pressure chemical vapor deposition (LPCVD) at a temperature of 620 ◦C, with a silane (SiH_4) flow rate of 40 sccm and pressure of 107 mTorr were used [3]. The thickness of the film is approximately 2 μm. After that, the films undergo a high-temperature phosphorus-diffusion step ($POCL_3$) at 950 ◦C for around 45 minutes to become heavily doped [3]. They are also subjected to *in situ* drive-in and annealing at 1000 ◦C for an hour [3]

List of References

1. Lin, L., Pisano, A. P., and Howe, R. T., 1997, "A Micro Strain Gauge with Mechanical Amplifier," J. Microelectromechanical Syst., 6(4), pp. 313–321.
2. B.P. Van Drieenhuizen, J.F.L. Goosen, P.J. French, R.F. Wolffenbuttel, Sens. Actuators, A 37/38 (1993) 756.
3. C.S. Pan, W. Hsu, J. Microelectromechanical Syst. 8 (1999) 200.
4. Q. He, Z.X. Luo, X.Y. Chen, Comparison of residual stress measurement in thin films using surface micromachining method, Thin Solid Films, Volume 516, Issue 16, 2008