Optimization of Design Parameters of a Novel MEMS Strain Sensor Used for Structural Health Monitoring of Highway Bridges

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Presented at the 2011 COMSOL Conference in Boston

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Outline

I. Background
  - Strain Sensors in the Literature
  - Conventional Applications and Measurements

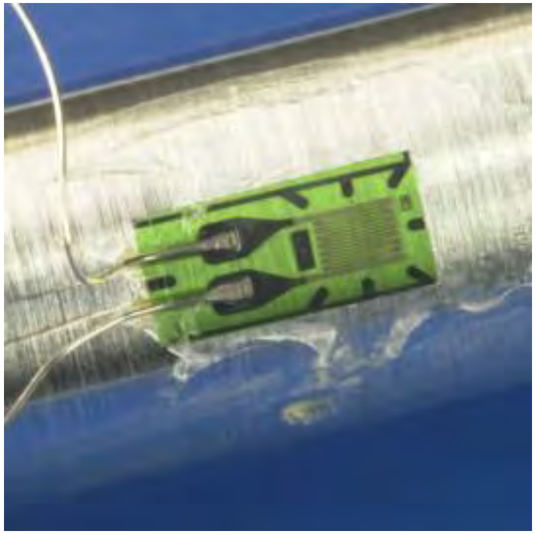
II. MEMS Strain Sensor
  - Design Parameters
  - Simulation
  - Optimization

III. Conclusion

IV. Future Work

Stain Sensor Types

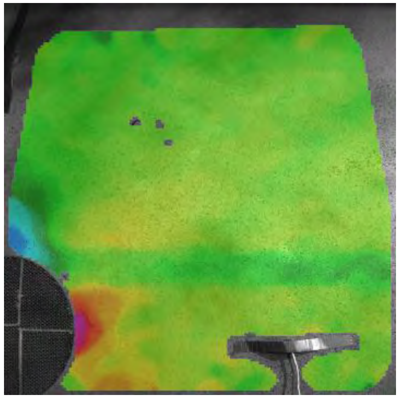
- Resistive Type
  - Metal Gauges
  - Semiconductor Sensors
- Optical
  - Digital Image Correlation and Tracking (DIC/DDIT or Strain Photogrammetry)
  - Fiber Optic Sensors



http://blog.prosig.com/2006/05/17/fatigue-durability-testing/

http://rebar.ecn.purdue.edu/ect/links/technologies/other/foptic.aspx

Strain Photogrammetry



Detecting Damage in Full-Scale Honeycomb Sandwich Composite Fuselage Panels through Frequency Response

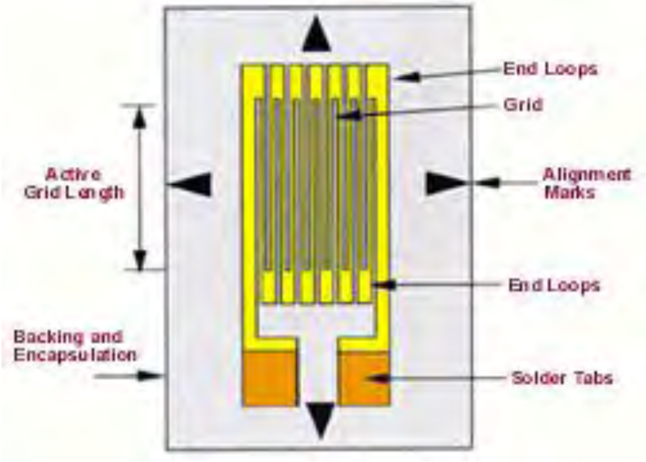
SPIE Smart Structures and Materials & Nondestructive Evaluation and Health Monitoring, San Diego, CA, 9 - 13 March 2008

Strain Sensors Comparison

Type of Strain Sensor		Pros	Cons
Resistive	Metal Gauges	• Low cost • Easy to operate	• Lower sensitivity
	Semiconductor sensors	• Higher sensitivity • Combination with multiple sensors on the same chip	• Temperature drift
Optical	DIC	• Very accurate • Fine strain gradient measurement	• Laboratory Only • Expensive
	Fiber Optic	• Wide range of data collection on single line	• Fragile • Expensive

Conventional Strain Gauges

- Characteristics
  - Foil Type Metal Strain Gauge
  - Gauge Factor = 2
  - Averaging over the area
  - Low cost



http://www.sensorland.com/HistPage003.html

- Disadvantages
  - Disability to detect strain gradient
  - Affecting strain field to where they has been attached
- Equations:

$$R = \frac{\rho L}{A} \Rightarrow \frac{\Delta R}{R} = \varepsilon(1+2\upsilon) + \frac{\Delta\rho}{\rho}$$

$$GF = \frac{\Delta R / R}{\varepsilon} = (1+2\upsilon) + \frac{\Delta\rho}{\varepsilon\rho} \qquad \frac{\Delta\rho_{ij}}{\rho} = \sum_{k,l} \pi_{ijkl} \mathrm{T}_{kl}$$

Piezoresistivity Coefficient

~0 for metal gauges

Piezoresistivity Coefficient of Silicon

π Values for the Single Silicon n doped of10^{-12} cm^2/dyne which shows that the maximum value at the direction of <100> as $\pi_l = 102 * 10^{-11}$ Pa^{-1} at room temp

$$GF = \frac{\Delta R / R}{\varepsilon} = E\pi_L \approx 165$$

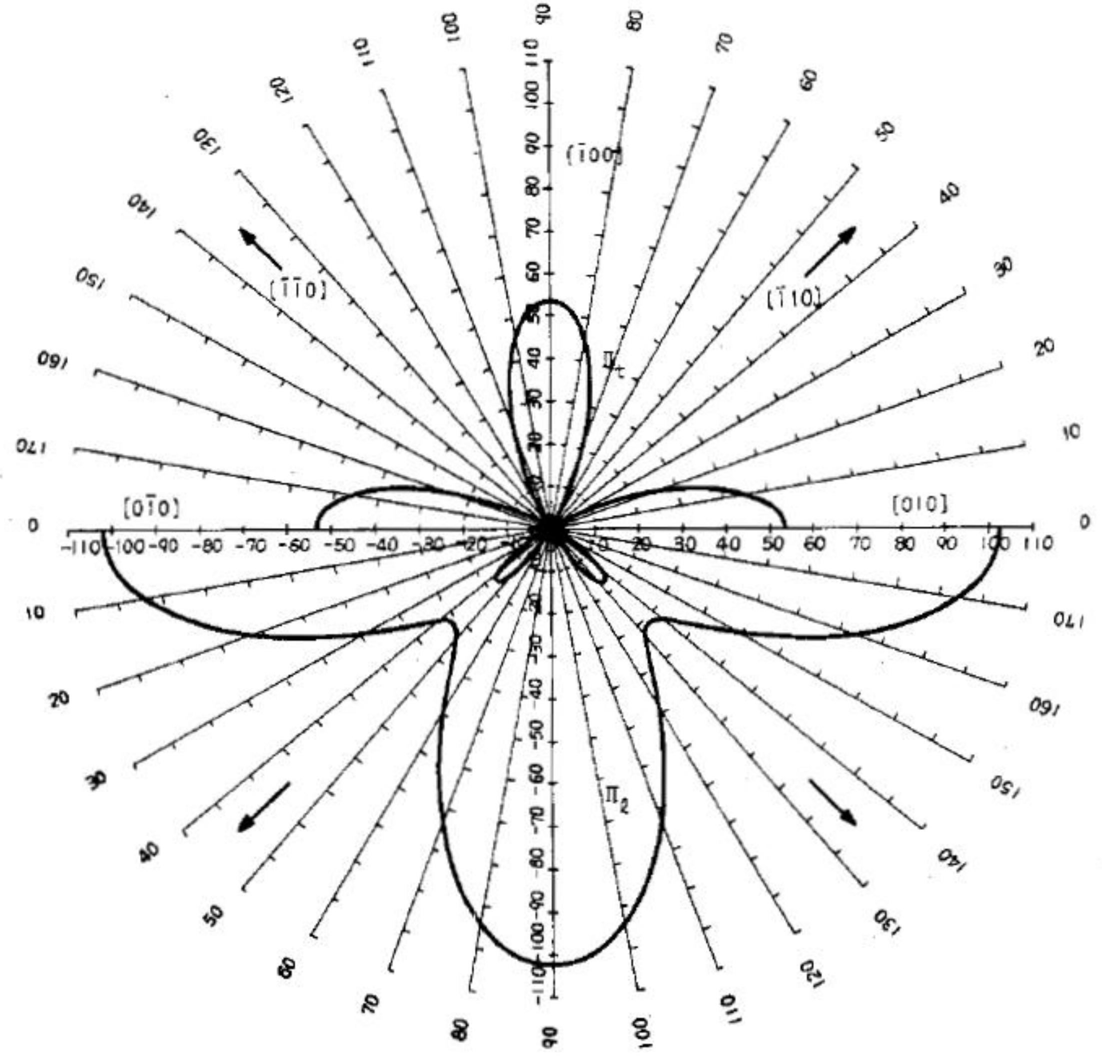


Fig. 2. Room temperature piezoresistance coefficients in the (001) plane of n-Si (10^{-12} cm^2/dyne).

A Graphical Representation of the Piezoresistance Coefficients in Silicon

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MEMS Strain Sensors (Semiconductor)

- Theoretical Achievements:
  - Gauge Factor = up to 165
- Characteristics
  - Very similar to conventional Strain Gauge
  - Gauge Factor = up to 20 (substrate effect)
  - Averaging over the area
  - Low cost
- Disadvantages
  - Disability to detect strain gradient
  - Affecting strain field to where they has been attached (packaging effect)
  - Anisotropy
  - Temperature dependent piezoresistive coefficients

Applications of Strain Sensor

Areas

- Highway Bridges
- Aerospace Industry
- Wind Turbines
- Any structure under loading

Type of Measurement:

  - Real Time Crack Monitoring
  - Continuous Strain Monitoring
  - Fracture Mechanics Research

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Design Goals

Overcoming the disadvantages of previous MEMS Strain Sensors

- Reduction of substrate affect as much as possible by forming the sensors on a thin diaphragm
- Amplification of Strain by *Geometric Features* of the sensor
- Ability to capture gradient of strain by the clip shape design.
- Lowering the effect of the strain sensor installation on the strain field of the localized regions.

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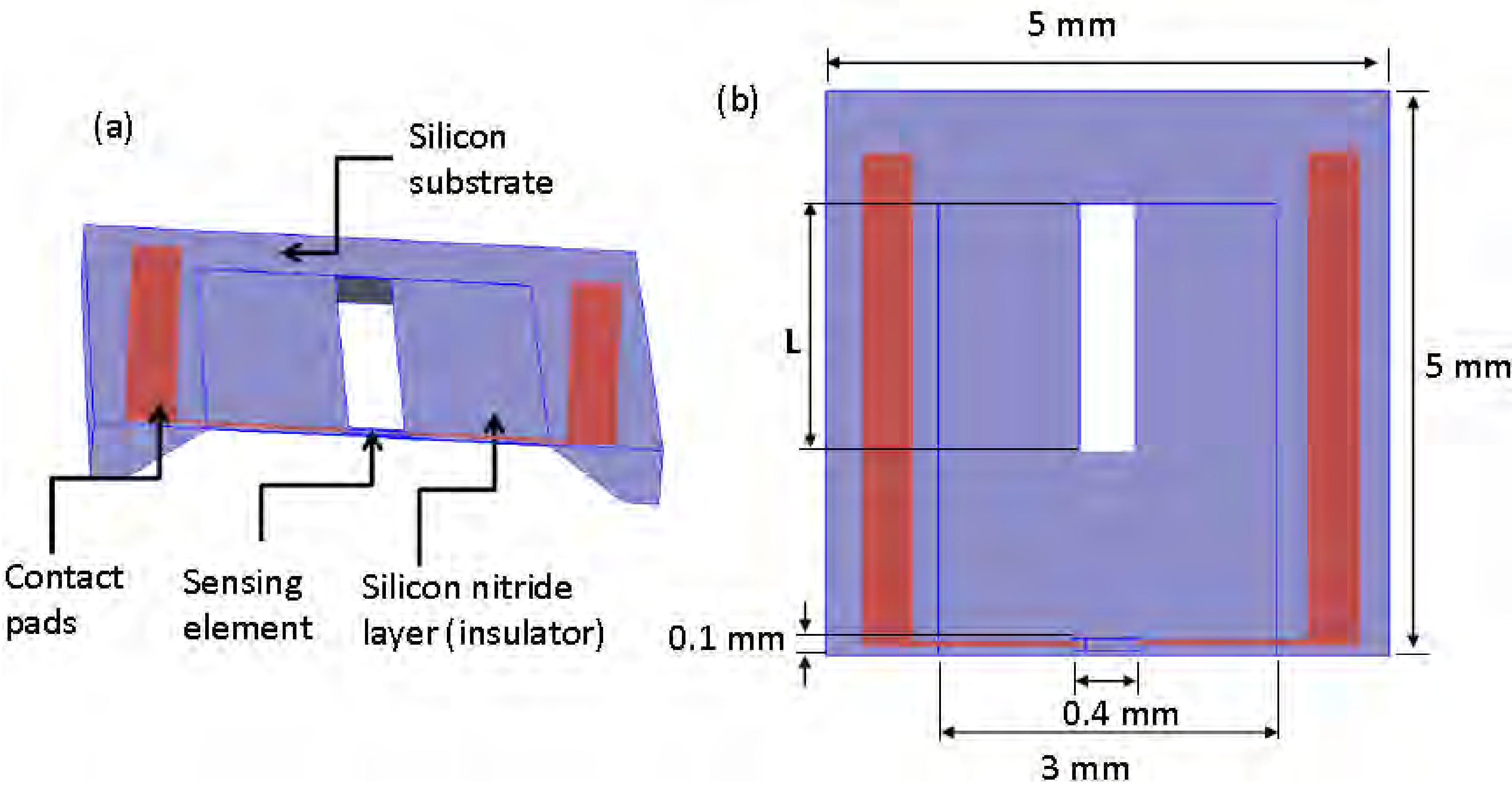
Design

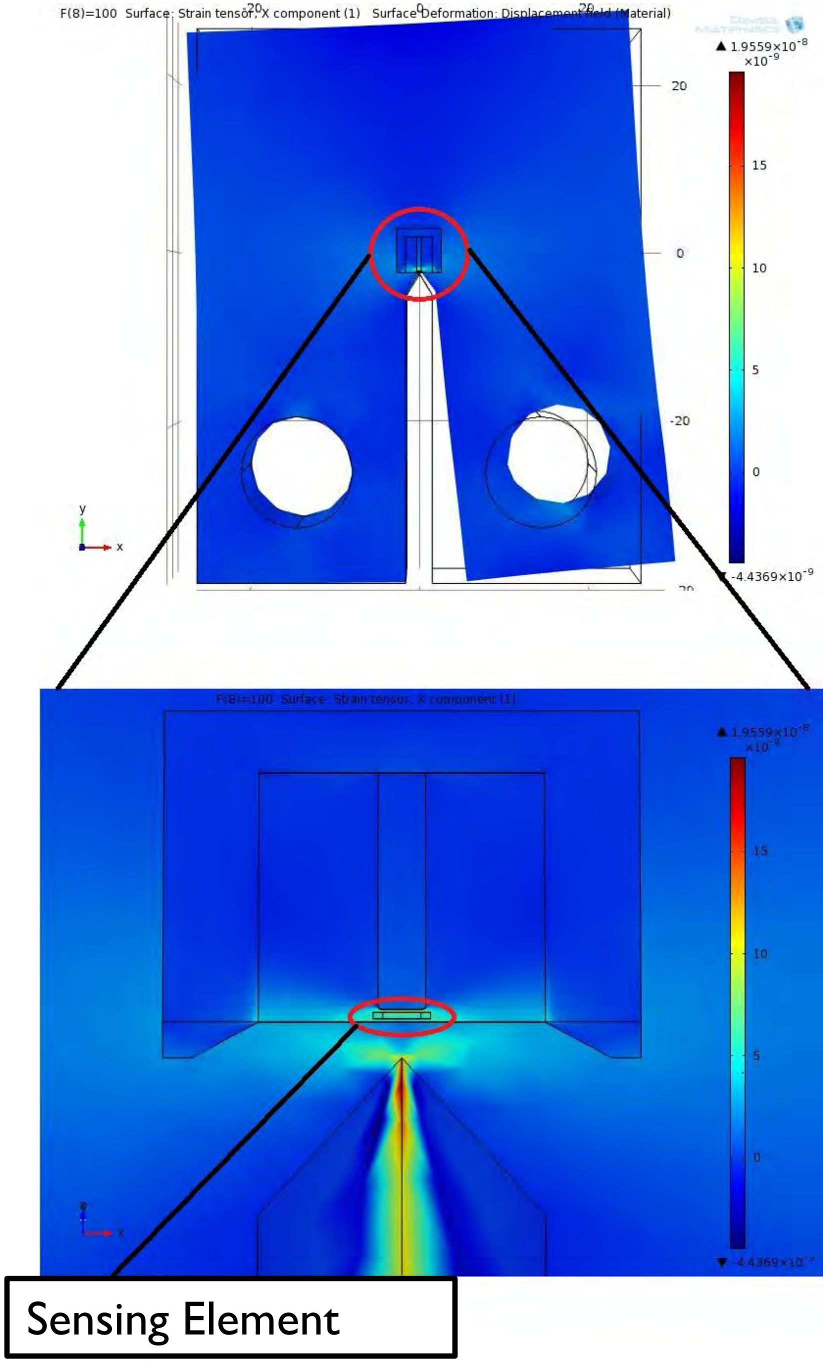


Geometry and design parameter

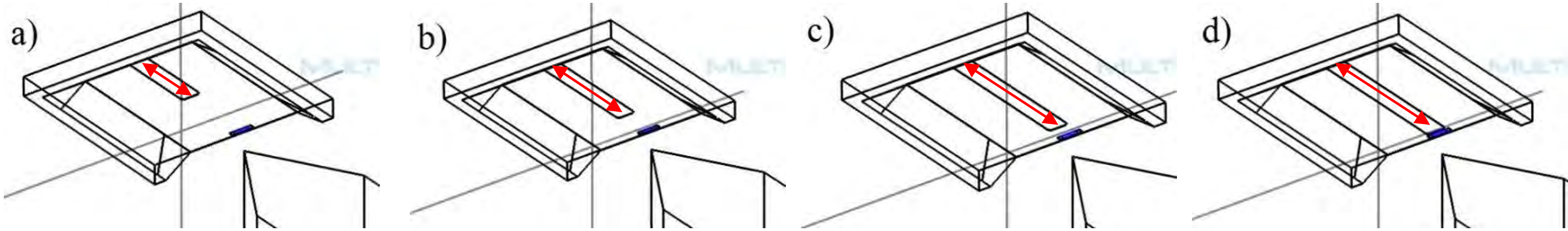
COMSOL Simulation

Physics – Solid and Electrical

- Solid Model Variables
  - Mesh
  - Loading
  - Boundary Condition
- Electrical Model Variables
  - Conductivity change: ρ =1e2[S/m]/(1+102e-11[Pa^-1]*solid.sx[Pa])
  - Electrical terminals (electrical BC)

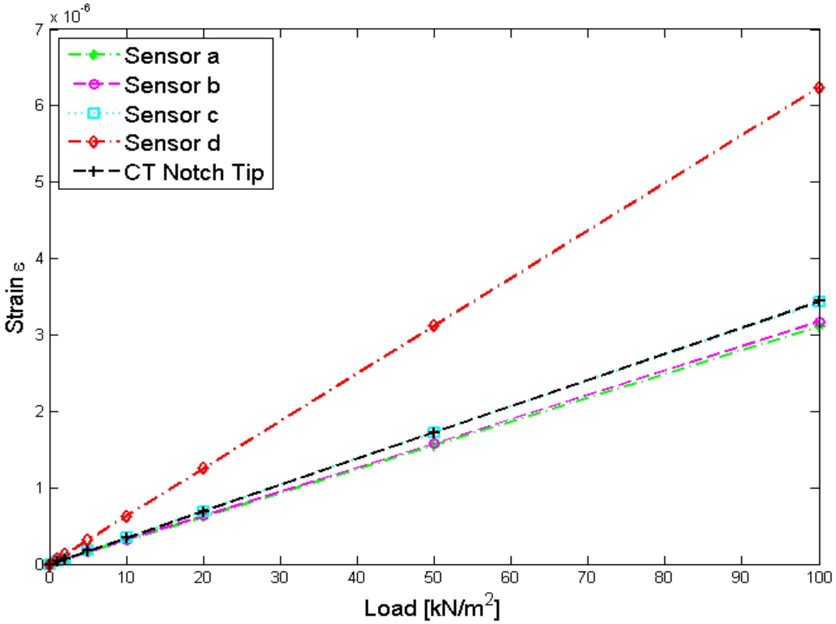


Geometry Optimization



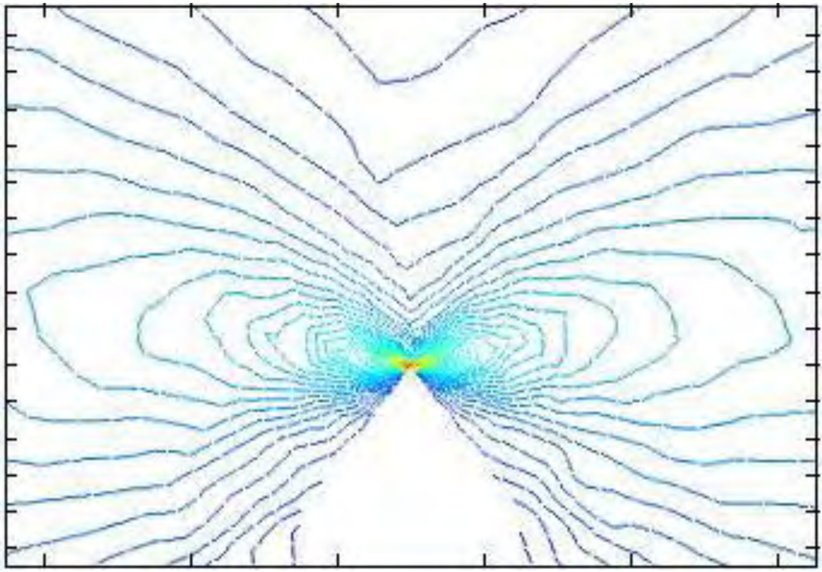
The Red arrows shows the length of etched geometry feature a)L=2mm b)L=3mm c)L=3.5mm d)L=3.8mm and the blue rectangle is the sensing element.

Strain vs load applied to the ends of the CT specimen for different lengths of the etched diaphragm.

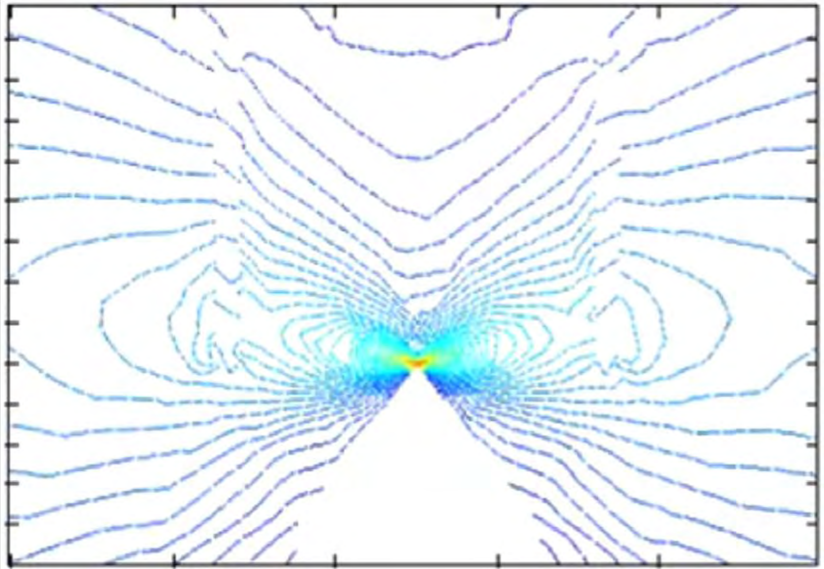


Effect of MEMS Sensor on Strain Distribution

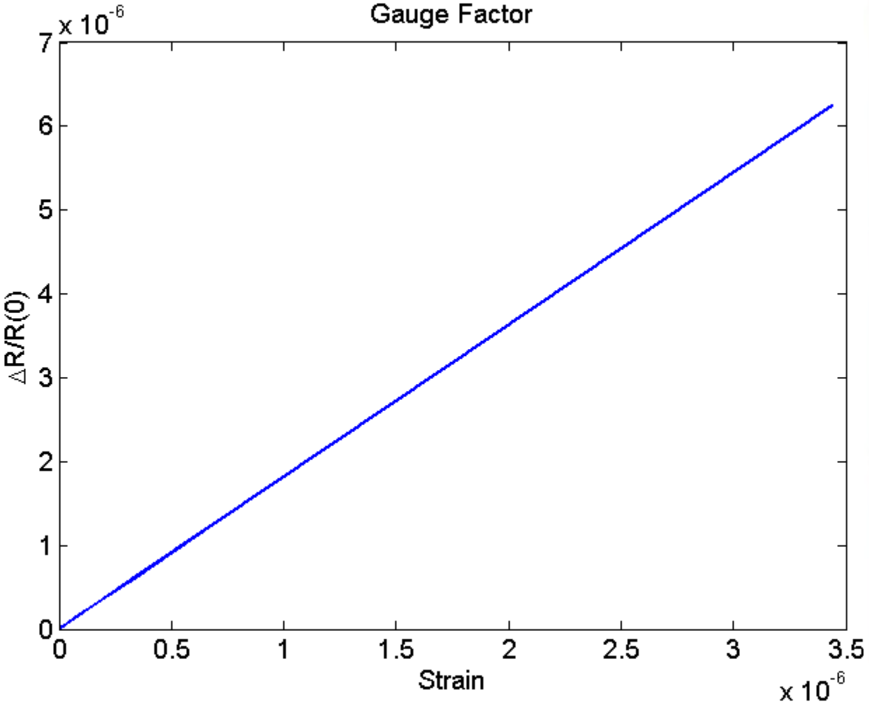
- Strain contour of back side of specimen which is not affected by sensor installation

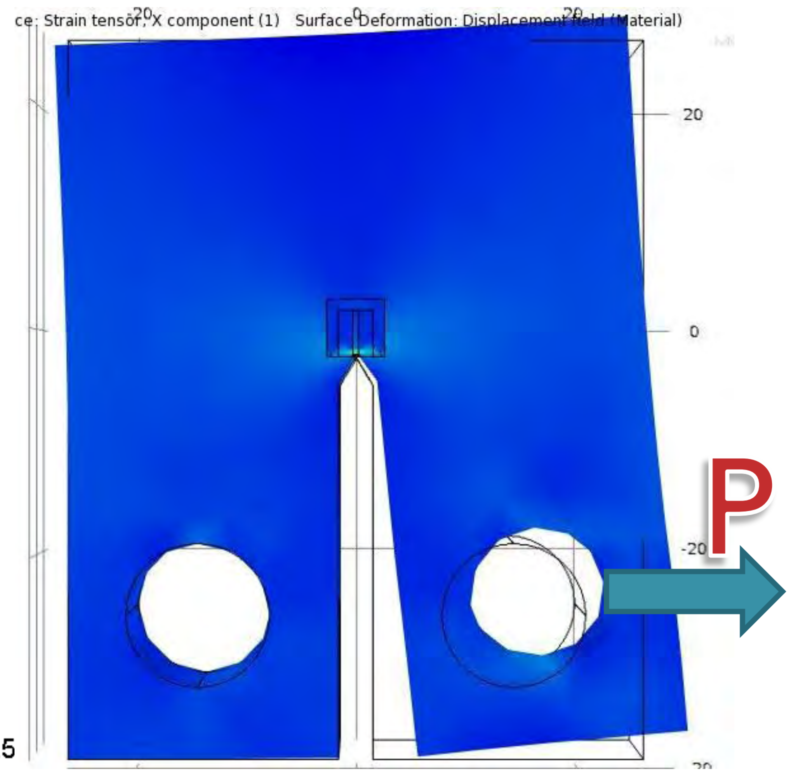


- Strain contour of front side of specimen which shows the effect of sensor installation on crack tip



Parametric Study





Actual gage factor of the MEMS strain sensor (GF_{act}) has been calculated to be 264 which is about 132 times higher than the gage factor of conventional metal strain gauges and about twice of theoretical gage factor of silicon (GF_{theo}) which is 135.

Conclusion

- The flexibility of MEMS manufacturing allows designing such a geometry that the sensor sensitivity is amplified at the sensor level.
- The results of COMSOL Multiphysics showed that the sensor sensitivity can be increased by about 100% by special geometry design.
- The presence of the MEMS package nearby the crack tip does not influence the strain distribution at highly gradient regions.
- This novel MEMS sensor has a small footprint so that the strain at highly gradient regions can be measured with negligible error.

Future Studies

- The sensor manufacturing using conventional IC methods (e.g. deposition, etching);
- The sensor characterization using impedance measurement and its comparison with conventional strain sensor and Digital Image Correlation (DIC) on a monotonically loaded CT specimen.

Thanks for listening,

Questions???