Piezoresistive Strain Gauges for use in Wireless Component Monitoring Systems

Stephen P. Olson[1], Dr. James Castracane[1], Ryk E. Spoor[2]

[1]College of Nanoscale Science and Engineering, University at Albany, State University of New York, 255 Fuller Road, Albany, NY 12203, Email: solson@uamail.albany.edu, jcastracane@uamail.albany.edu
[2]International Electronic Machines Corporation (IEM). 60 Fourth Avenue, Albany, NY 12202, Email: rspoor@iem.net

Outline

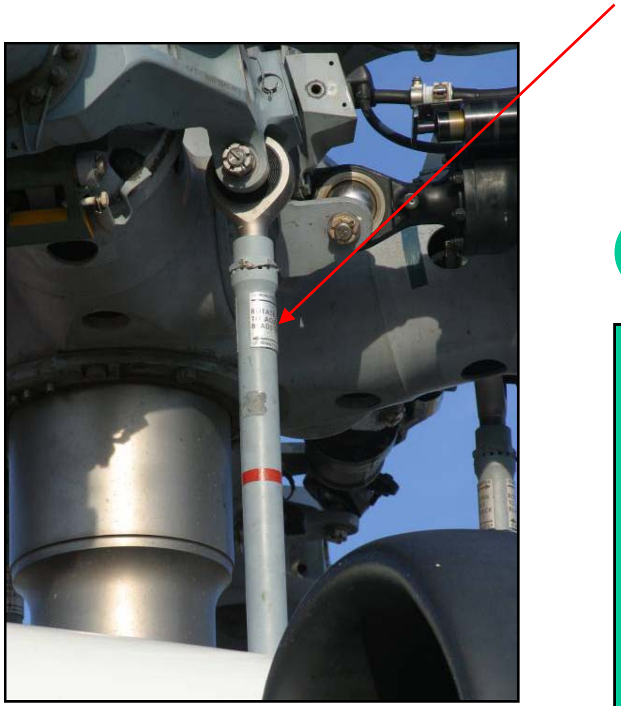
- Strain monitoring systems for rotating helicopter parts
- Strain gauge requirements – *Low power consumption*
- Piezoresistive strain gauges
- Strain gauge design and fabrication flow
- Test setup
- Strain response simulation
- Strain gauge measurements - *Response and noise*
- Conclusions and acknowledgements

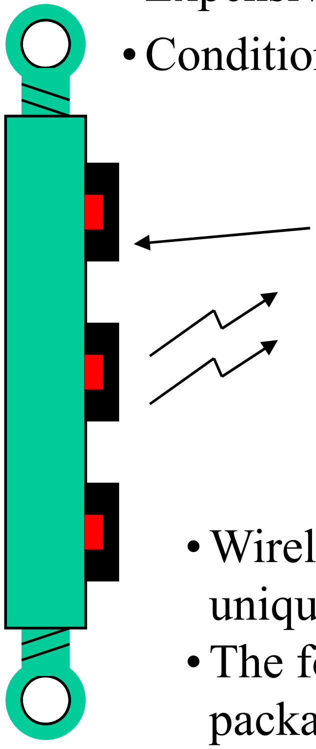
Component monitoring

Overall Goal:

Reduce unnecessary prescribed maintenance schedules by providing real-time data on component condition.

- Pitch link controls the angle of the rotor blade as it spins
- One of many parts critical for controlled flight
- Currently these parts are replaced based on usage hours
  - Expensive
  - Condition is not known while in service





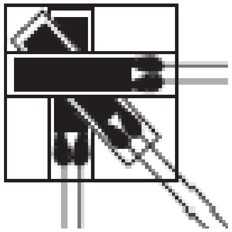
Wireless strain monitoring tags

- Power system
- Data gathering and signal conditioning
- RF transmitter
- Strain gauge

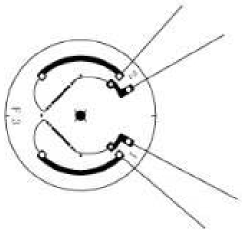
- Wireless system and properties of the pitch link place unique requirements on the strain gauge
- The focus of this project is to design, fabricate and package strain gauge devices for this system

Strain gauge requirements

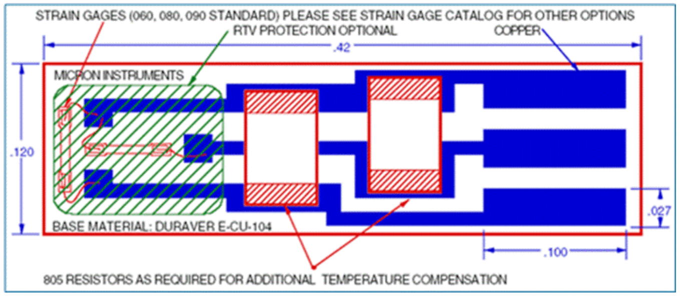
Company	Type	G	R (ohm)	Size
Omega	Metal foil	2	120	5x6mm
Soltec Corporation	Semiconductor	-100	120	11mm dia
Micron	Semiconductor	100..155	540..1050	10.6x3



Omega[1]



Soltec[2]



Micron[3]

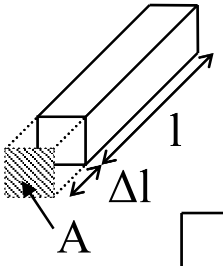
Requirements for the sensor:

- Multi-axis
- Power consumption <100µW, preferably 10µW
- 5 µε resolution, 10 kHz measurement bandwidth
- Small size, target size for entire tag is 12.7mm square (sensor, power system, readout electronics and RF transmitter)
- Low power requires a large gauge factor (sensitivity), large resistance (~100kΩ)
- Operational temperature range -20 to 70 ºC

1. www.omega.com/pptst/Rosettes_Stackedgrid_Strain_SG.html
2. www.solteccorp.com/products.aspx?catid=48
3. www.microninstruments.com/products/gages/ssgh-halfbackgage.htm

Resistive strain gauges

$$R = \frac{\rho l}{A}$$



$$\frac{\Delta R}{R} = G\left(\frac{\Delta L}{L}\right)$$

- Conductors change resistance when strained
- Gauge factor is the sensitivity of the gauge

- Resistance of a wire is proportional to its length
- Poisson ratio reduces the cross-sectional area, increasing the resistance
- Piezoresistive materials change resistivity when a stress is applied, changing the resistance of the gauge

$$G = \underbrace{1 + 2\nu}_{\sim 2} + \underbrace{\pi_l E}_{>100}$$

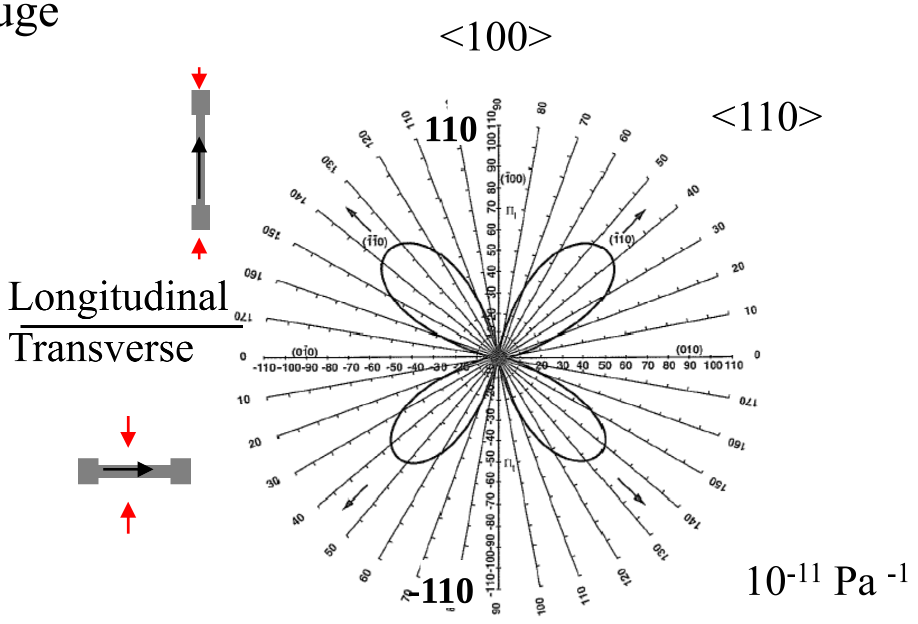
For a strain gauge with a rectangular cross section

G Gauge Factor

E Young’s modulus

ν Poisson ratio

π_l Piezoresistive coefficient



P-type Silicon piezoresistance coefficients

Marc J. Madou, **Fundamentals of Microfabrication: The Science of Miniaturization,** CRC; 2 edition (March 13, 2002)

Noise sources

- Noise will limit sensor resolution
- Johnson or thermal noise
  - Frequency independent
  - Depends on resistance, temperature and measurement bandwidth
  - k_B Boltzmann's constant
  - R=100kΩ, T=300K, measurement bandwidth=10kHz

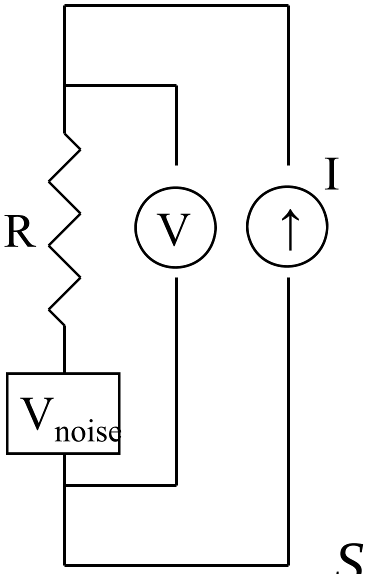
$$V_{Thermal} = \sqrt{k_B R\, T(f_{\max} - f_{\min})} = 2\times10^{-6}\ V_{RMS}$$

- 1/f noise
  - Frequency dependent
  - Hooge noise model depends on the number of carriers, bias voltage, and measurement frequency
  - N= $9\text{x}10^8$, $\alpha=1\text{x}10^{-5}$, $V_b=1\text{V}$, $f_{max}/f_{min}=10{,}000$

$$V_{1/f} = \sqrt{\frac{\alpha V_b^2}{N}\ln\left(\frac{f_{\max}}{f_{\min}}\right)} = 3.2\times10^{-7}\ V_{RMS}$$

Harkey, J.A. Kenny, T.W, *Journal of microelectromechanical systems*, 9 no. 2 2000

Signal to noise



$$V_{out} = V_{noise} + V_{signal}$$

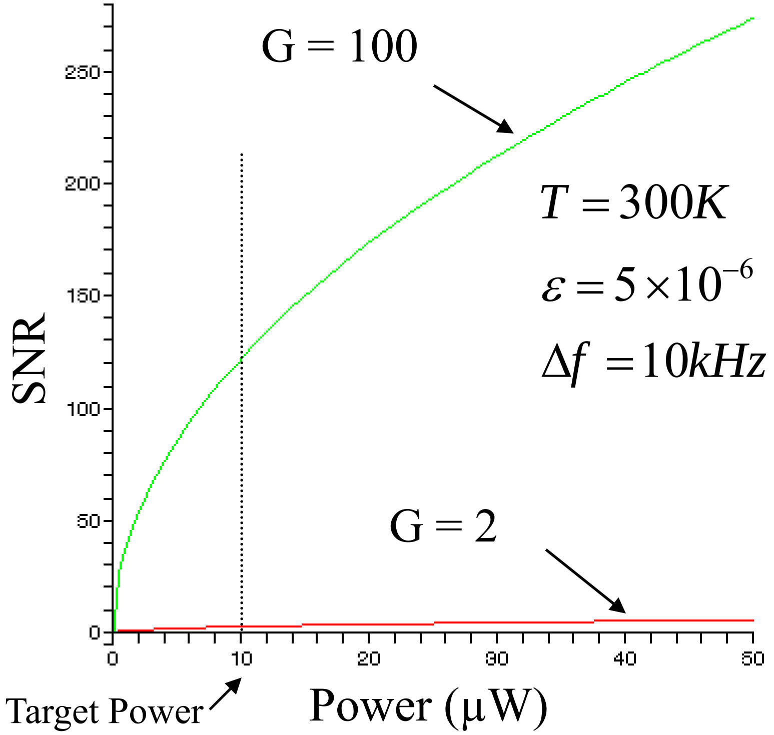
$$V_{noise} = \sqrt{4k_B T \Delta f R}$$

$$V_{signal} = I(R + \Delta R)$$

$$\frac{\Delta R}{R} = G\varepsilon$$

$$I = \sqrt{\frac{P}{R}}$$

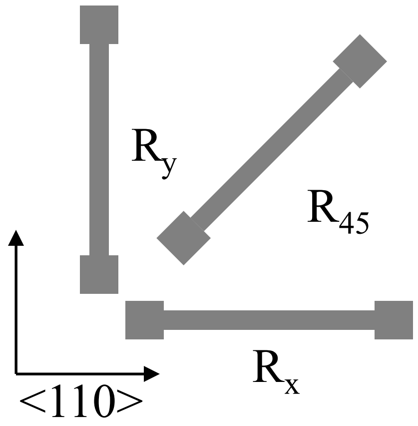
$$\frac{Signal}{Noise} = \frac{G\varepsilon}{\sqrt{4k_B T \Delta F}}\sqrt{P}$$



- Plot shows the signal to Johnson noise ratio for a 5 microstrain signal as a function of power
- Large gauge factor will be required for low power operation
- Resistance does not affect signal to Johnson noise ratio

Silicon rosette sensor

Sensor response to arbitrary stress state [1]

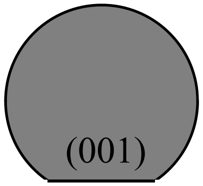


$$\frac{\Delta R_x}{R_x} = \pi_l\sigma_x + \pi_t\sigma_y + \pi_{12}\sigma_z$$

$$\frac{\Delta R_y}{R_y} = \pi_t\sigma_x + \pi_l\sigma_y + \pi_{12}\sigma_z$$

$$\frac{\Delta R_{45}}{R_{45}} = \pi_s(\sigma_x + \sigma_y) + \pi_d\tau_{xy} + \pi_{12}\sigma_z$$

$$\pi_l = \tfrac{1}{2}(\pi_{11} + \pi_{12} + \pi_{44})$$
$$\pi_t = \tfrac{1}{2}(\pi_{11} + \pi_{12} - \pi_{44})$$
$$\pi_s = \tfrac{1}{2}(\pi_{11} + \pi_{12})$$
$$\pi_d = (\pi_{11} - \pi_{12})$$



[2]

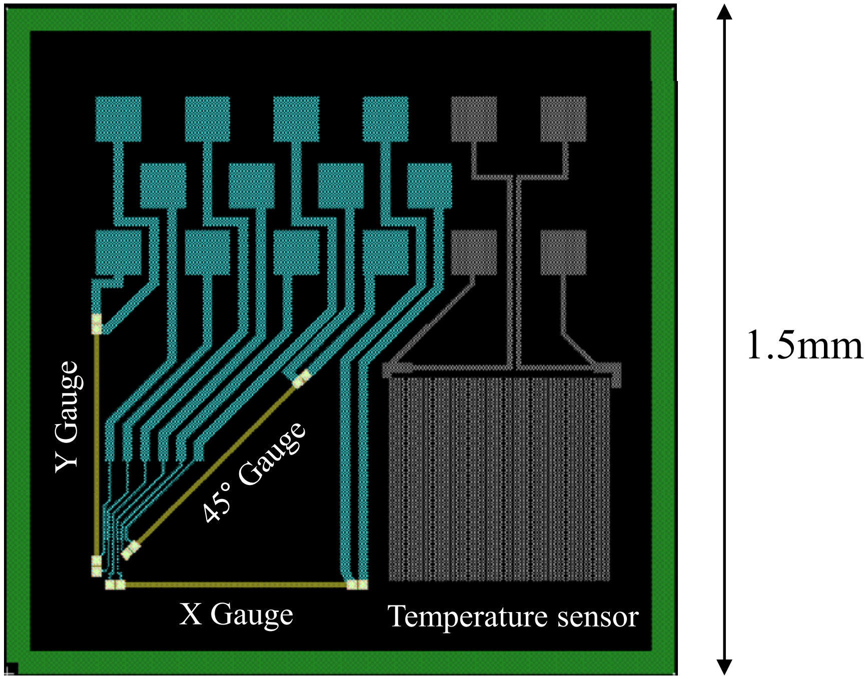
Dopant	π_l	π_t	π_s	π_d
P	71.8	-66.3	2.75	7.7
N	-31.2	-17.6	-24.4	-155.6

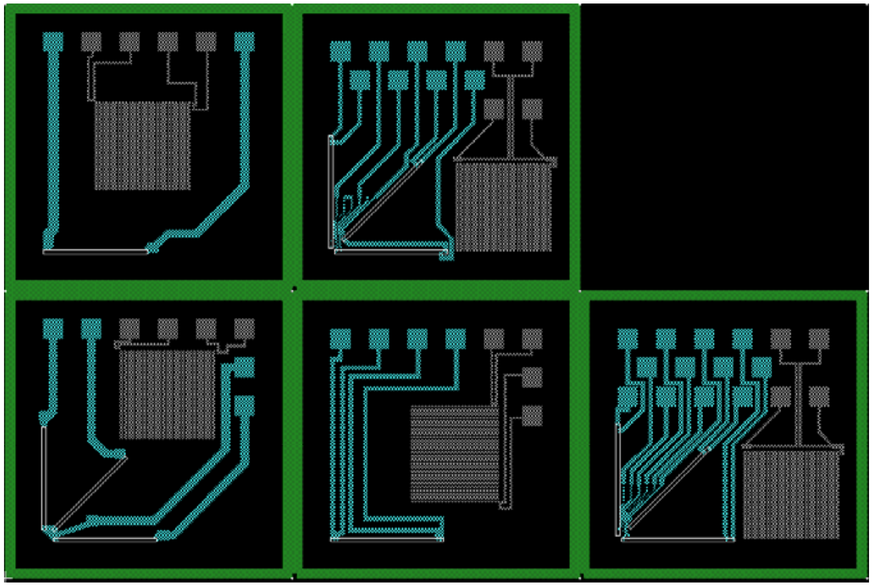
All units 10^{-11} Pa $^{-1}$

- Sensor will respond to X, Y, Z and in plane shear stress
- Three measurements can resolve X, Y and in plane shear stress if z stress is zero
- Best sensitivity will be achieved using P type x and y sensors and N type 45 degree sensors

1. D. A. Bittle, J. C. Suhling, R. E. Beaty, R. C. Jaeger, and R.W. Johnson, "**Piezoresistive stress sensors for structural analysis of electronic packages**", *Journal of electronic packaging*, Vol 113(3), 1991, pp. 203-215
2. Simon M. Sze, **Semiconductor Sensors,** *Wiley-Interscience* (October 1994)

Strain gauge designs





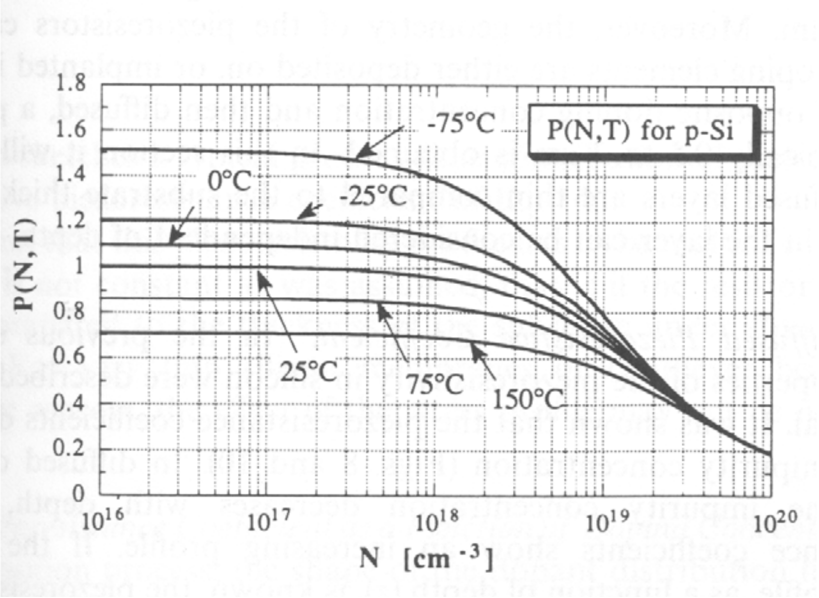
Strain gauge design:

- 1.5 mm die
- Sensors formed by boron ion implant
- 0-45-90 rosette configuration
- 4 wire readout
- Integrated Pt temperature sensor

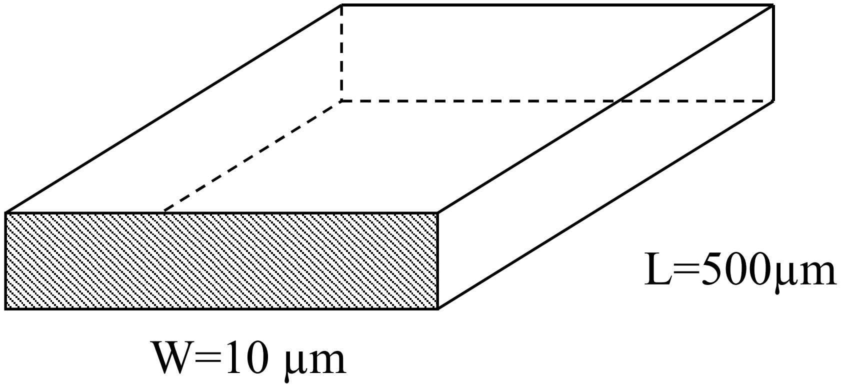
Strain gauge variations:

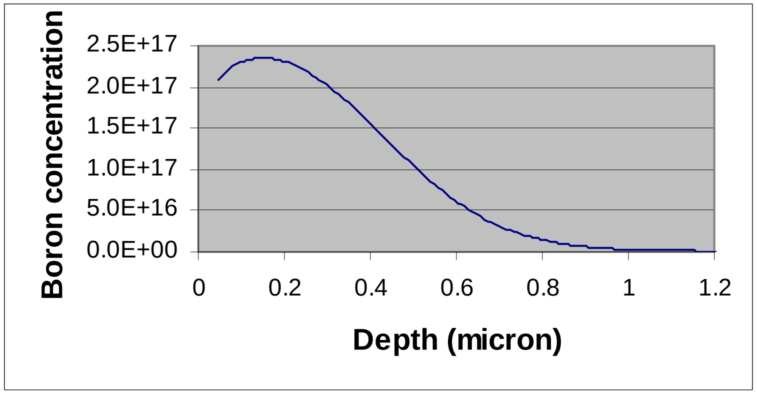
- 2 and 4 contact gauges
- Single and multi-axis configuration
- Multi axis gauges in series

Sensing element design



- Graph shows piezoresistive factor(P) as a function of boron concentration and temperature
- Piezoresistive coefficient (π_1)= (P) ($72x10^{-11}$ m^2/N)



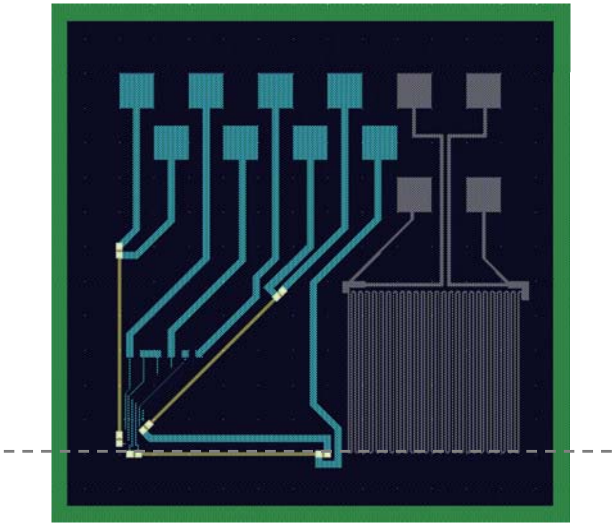


- To achieve maximum sensitivity, implant dose should be below 10^{18} B/cm^3
- Implant parameters, 1.29e13 B/cm^2 chosen based on Suprem3 calculations to achieve a sheet resistivity of 200 Ω/square

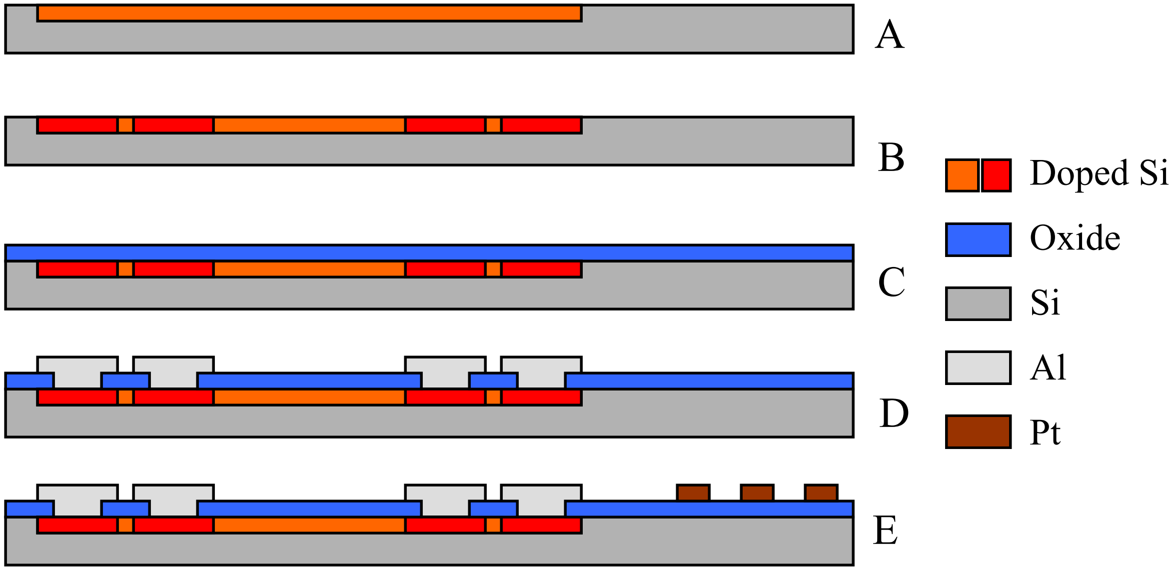
- Graph shows boron distribution after implant and anneal
- Suprem3 simulation software calculates a sheet resistivity of 2000 ohms / square
- 50 square resistor is expected to be 100kΩ

Simon M. Sze, **Semiconductor Sensors,** *Wiley-Interscience* (October 1994)

Gauge design and fabrication flow



CAD layout showing location of the cross sections



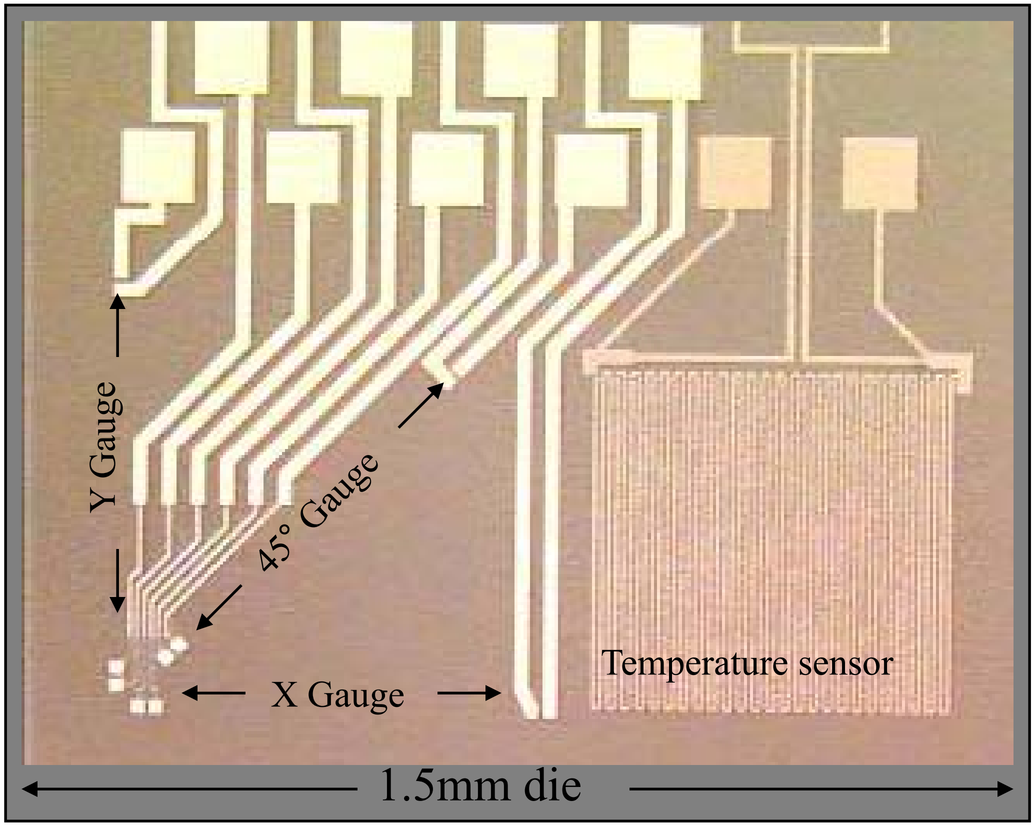
Process flow cross section diagrams

Process Flow Steps:

Start with N type (100) wafer (1-10 Ω-cm)

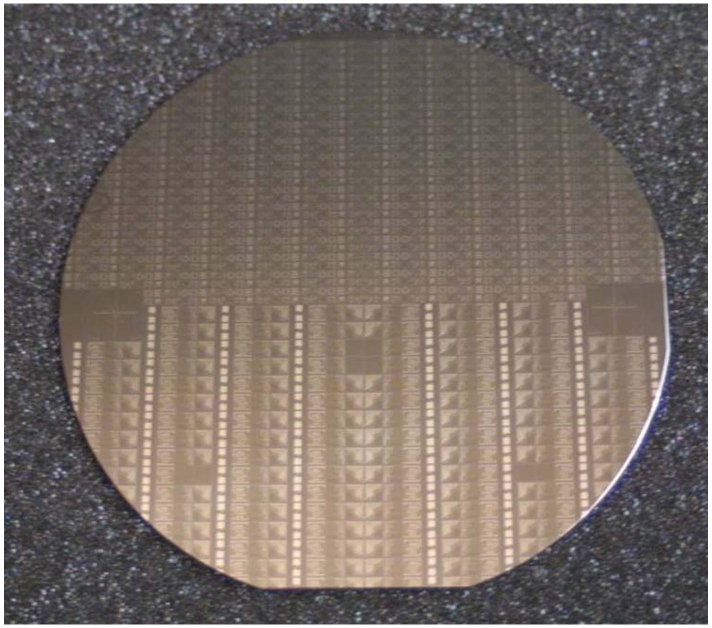
A. Sensors are formed by boron ion implantation
B. Contact areas are made P+ using a second implant
C. Wafers are annealed in oxygen to activate the dopant and form 500Å of oxide
D. Oxide is patterned to form contact holes. 1000Å Al is deposited and patterned
E. 1000Å Pt is deposited and patterned to form the temperature sensor
F. Wafers are annealed at 450°C to form the Al –Si contacts (not shown)

Fabricated strain gauges

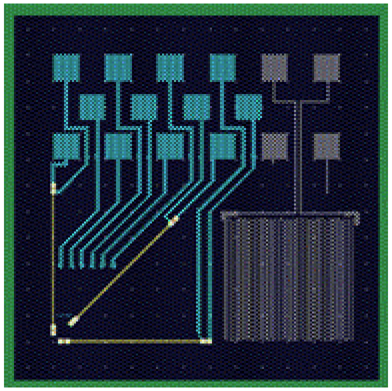


Optical image showing 3 gauge die with temperature sensor

Strain gauge devices have been fabricated at the College of Nanoscale Science and Engineering

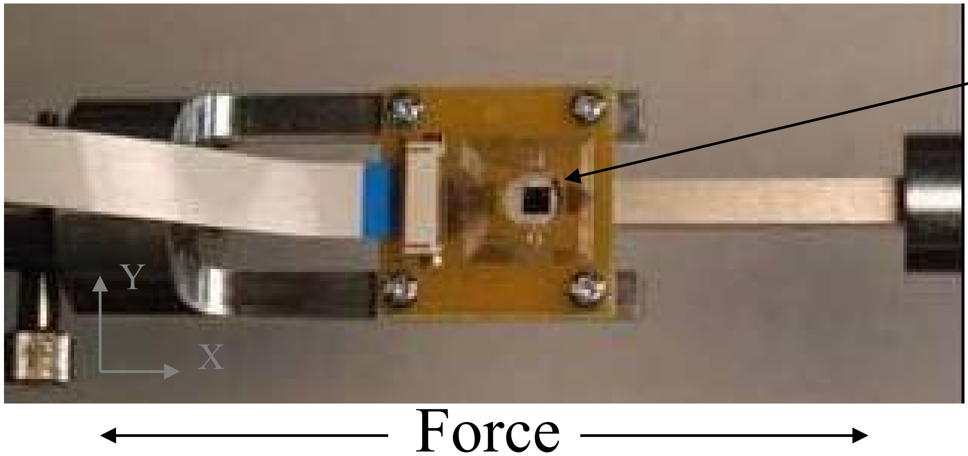


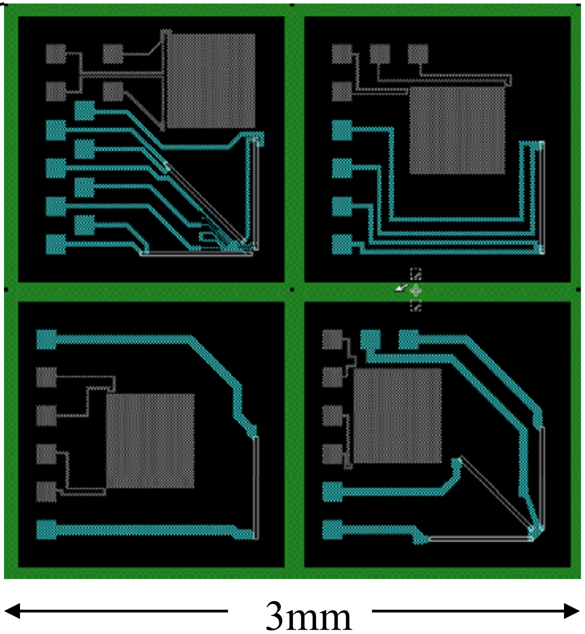
Optical image of finished 100mm wafer



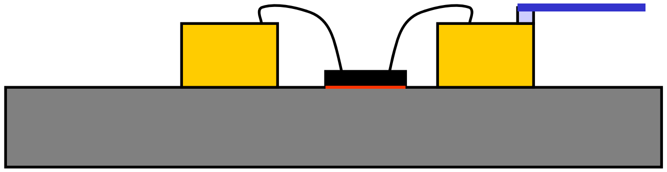
CAD layout of strain gauge die

Test setup

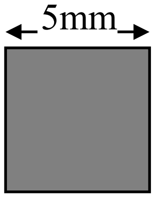




Strain gauge die

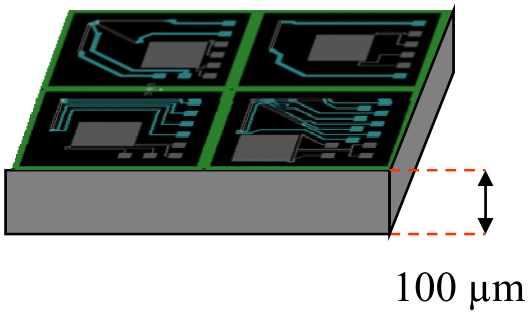


X-Z Cross section

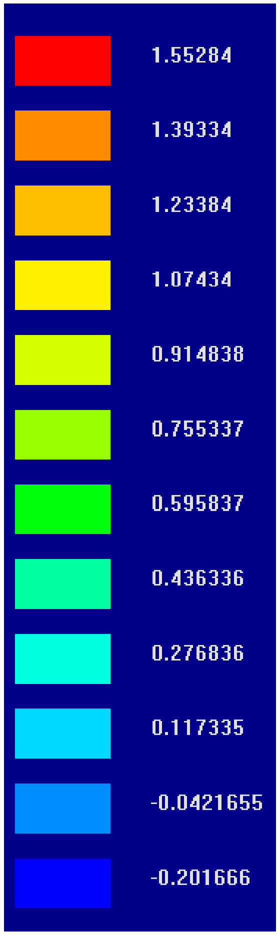


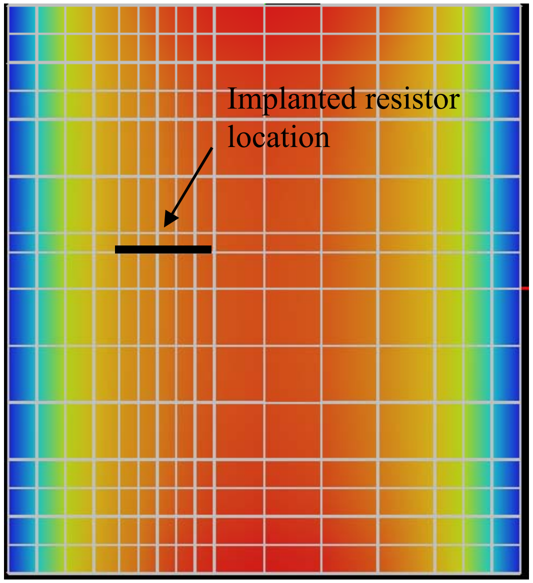
Y-Z Cross section

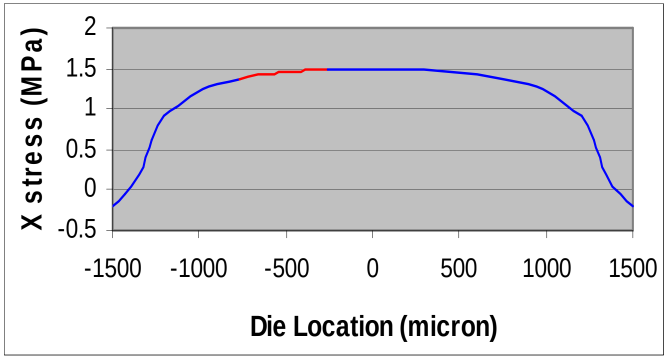
- Sets of four of strain gauges are diced into 3mm test dies
- Test dies are thinned form ~550µm to 100µm
- Bonded to a 15-5PH stainless steel test beam
- Test beam is square in cross section, 5mm on a side
- Wirebond connections are made to a printed circuit board



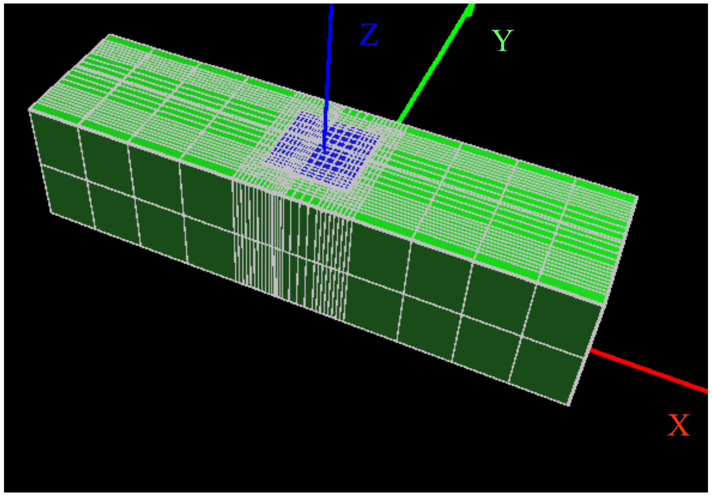
Stress simulation

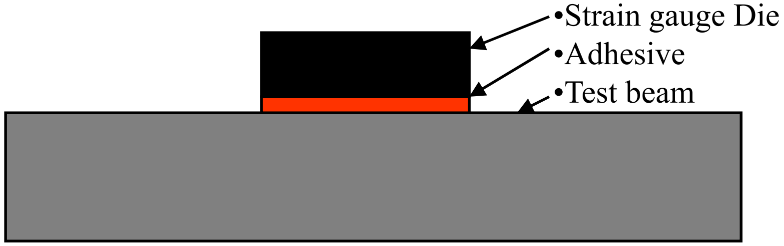






Stress (MPa)
In the direction
of the beam (X
direction)

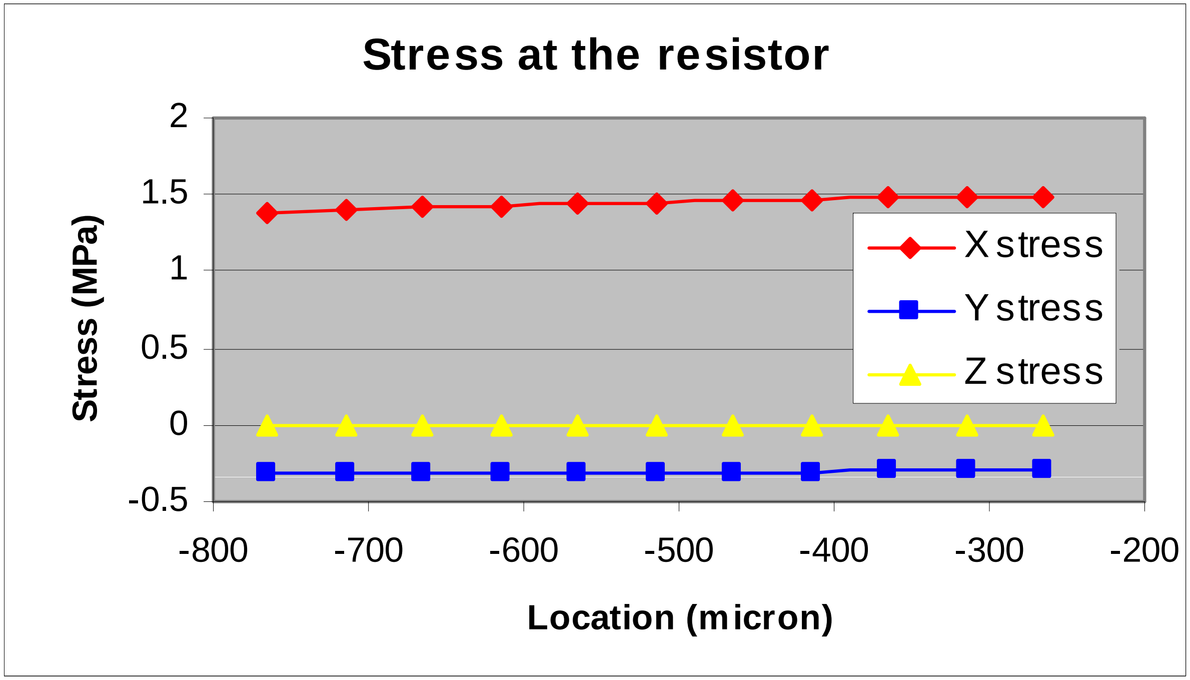




- Solid model includes the test beam, adhesive, and strain gauge die

- Finite element software Intellisuite is used to simulate the stress distribution on the surface of the strain gauge
- 50N is applied to the test beam (~10 με)
- Plot above shows the X direction stress at the surface of the die

Gauge factor extraction



$$\frac{\Delta R_x}{R_x} = \pi_l \sigma_x + \pi_t \sigma_y + \pi_{12} \sigma_z$$

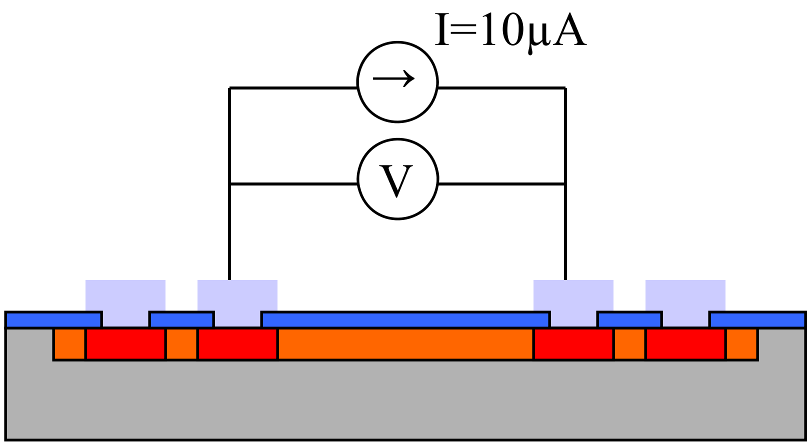
$$\frac{\Delta R}{R} = G\left(\frac{\Delta L}{L}\right)$$

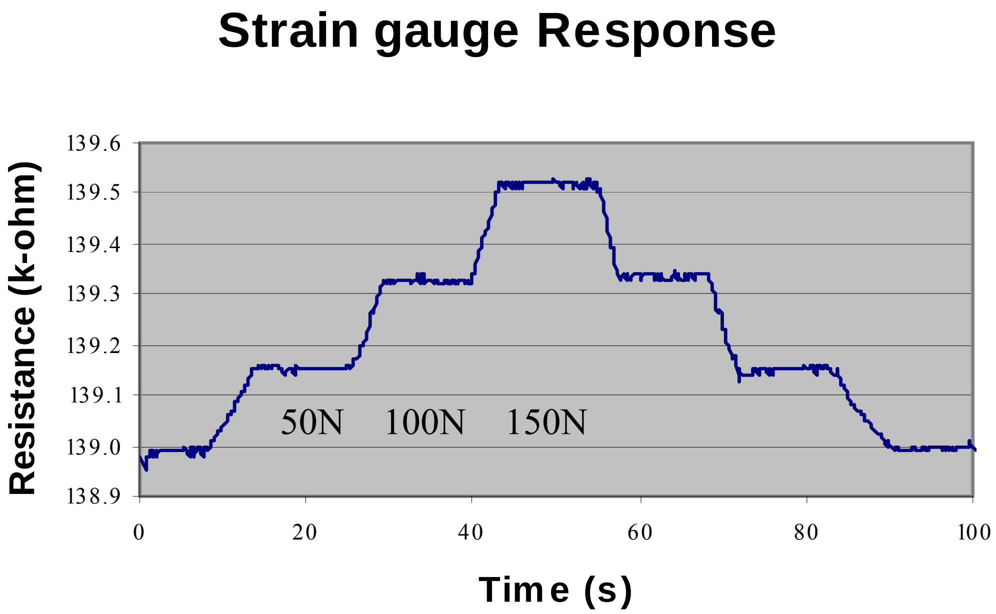
- Average X stress: 1.44 MPa
- Average Y stress: -0.309 MPa
- Average Z stress: 1.76 X 10^{-4}MPa
- $^{\Delta L}/_{L}$: 10.2με

- Graphs show the X and Y stress along thee implanted resistor
- Gauge factor is calculated by using average X and Y direction stress from the simulation

- Expected gauge factor: 121

Strain gauge response

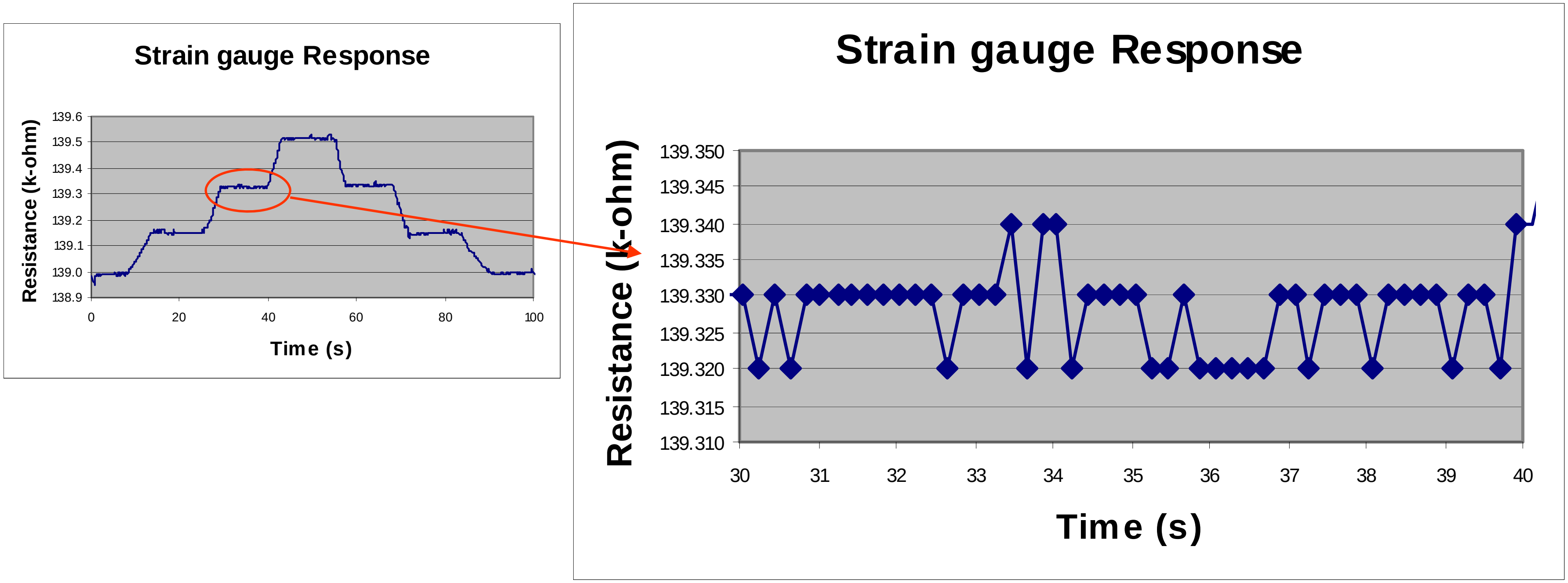




- Strain gauge resistance is measured by driving 10µA of current and measuring the voltage
- 14 µW of power is dissipated in the gauge during the measurement

- Loads of 50, 100, and 150N are applied to the test beam.
- 50N load produces ~10µε in the test beam
- Calculated from the data in the graph, the gauge factor is ~120

Noise



	Target	Measured
Gauge Factor	>100	120
Resistance	~100 kΩ	139 kΩ
Resolution	5 με	Acceptable

- Noise in the trace is ~7 ohms RMS, at a gauge factor of 120, this represents ~0.5 microstrain RMS.
- Analog to digital steps in data prevent further noise analysis
- Measured noise level is suitable for measuring strain at the 5με level

Summary

- Large gauge factor is required for sensing strain at low powers
- Piezoresistive silicon is a natural choice for its large gauge factor and ability to be batch fabricated
- Single die, multi-axis strain gauges have been designed and fabricated
- Test data shows that the gauge is suitable for measuring 5 microstrain while dissipating only 14 µW of power

Acknowledgement

We would like to acknowledge Dr. Hassaram Bakhru for his help with ion implantation as well as Lawrence Clow and Barry Treloar for their help and useful discussion.

This work was supported in part by the United States Navy, NAVAIR Contract N68335-05-C-0216

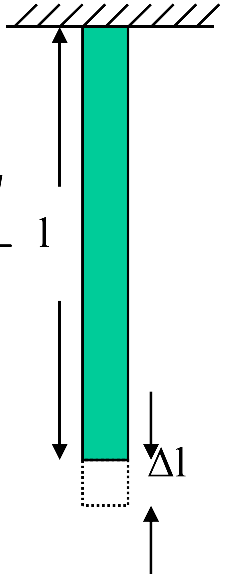
Thank you for your attention

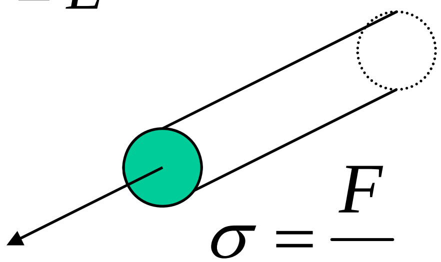
Stress and strain

Strain ⟷ Stress

$$\frac{\sigma}{\varepsilon} = E$$

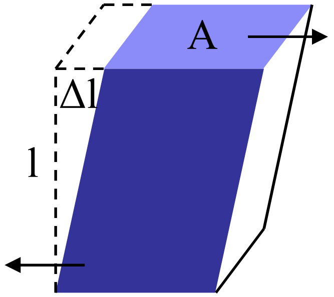
$$\varepsilon = \frac{\Delta l}{l}$$





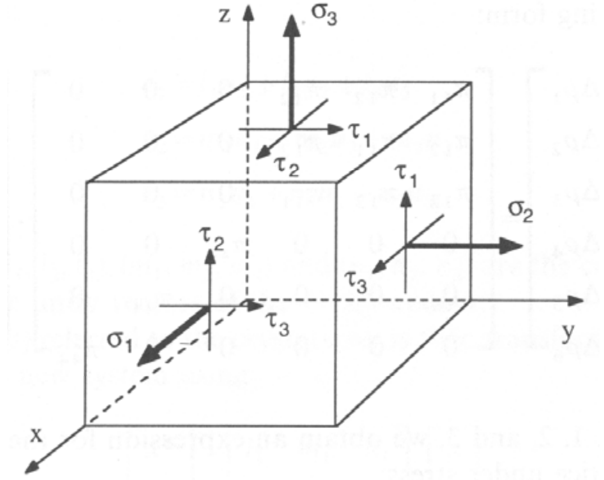
$$\sigma = \frac{F}{A}$$

σ Stress
F force
A cross sectional area
ε Strain
E Young’s modulus



Shear stress τ=F/A
Shear Strain γ= Δl/l

[1]



- Stress: Normalized force applied to a part
- Strain: Normalized extension of a part
- Stress and strain are related by the Young’s modulus material property
- µstrain = 1 part per million extension

1. Simon M. Sze, **Semiconductor Sensors,** *Wiley-Interscience* (October 1994)