Advanced MEMS and Microsystems

Dr. Danick Briand & Prof. Guillermo Villanueva

Course content and schedule

Dates	Topics	Lecturers
18.02	Introduction	D. Briand / G. Villanueva
	Transducers review: pre-recorded lectures	
25.02	Sensors part I	D. Briand
	Exercices	
04.03	Sensors part II	D. Briand
	Industrial seminar #1	
11.03	Students presentations	D. Briand / G. Villanueva
18.03	Actuators and Optical MEMS	D. Briand
	Industrial seminar #2	
25.03	Acoustic and Ultrasonic MEMS	G. Villanueva
	Industrial seminar #3	
01.04	RF-MEMS	G. Villanueva
08.04	NEMS	G. Villanueva
15.04	Interactive session	D. Briand / G. Villanueva
29.04	Thermal and gas sensors	D. Briand
	Industrial seminar #4	
06.05	Packaging	D. Briand
13.05	Packaging	D. Briand
	Industrial seminar #5	
20.05	PowerMEMS	D. Briand
	Industrial seminar #6	
27.05	Quiz + oral exam instructions	All
	Evaluation of the course	

Announcements

TODAY FEBRUARY 25

- **Lecture 2 Sensors Part I**
- **Exercises on Sensors Parts I & II available on the moodle**

NEXT WEEK MARCH 4

- **Seminar 1 – Safran Sensing Technologies**
- **Graded with a list of questions to answer on the moodle**

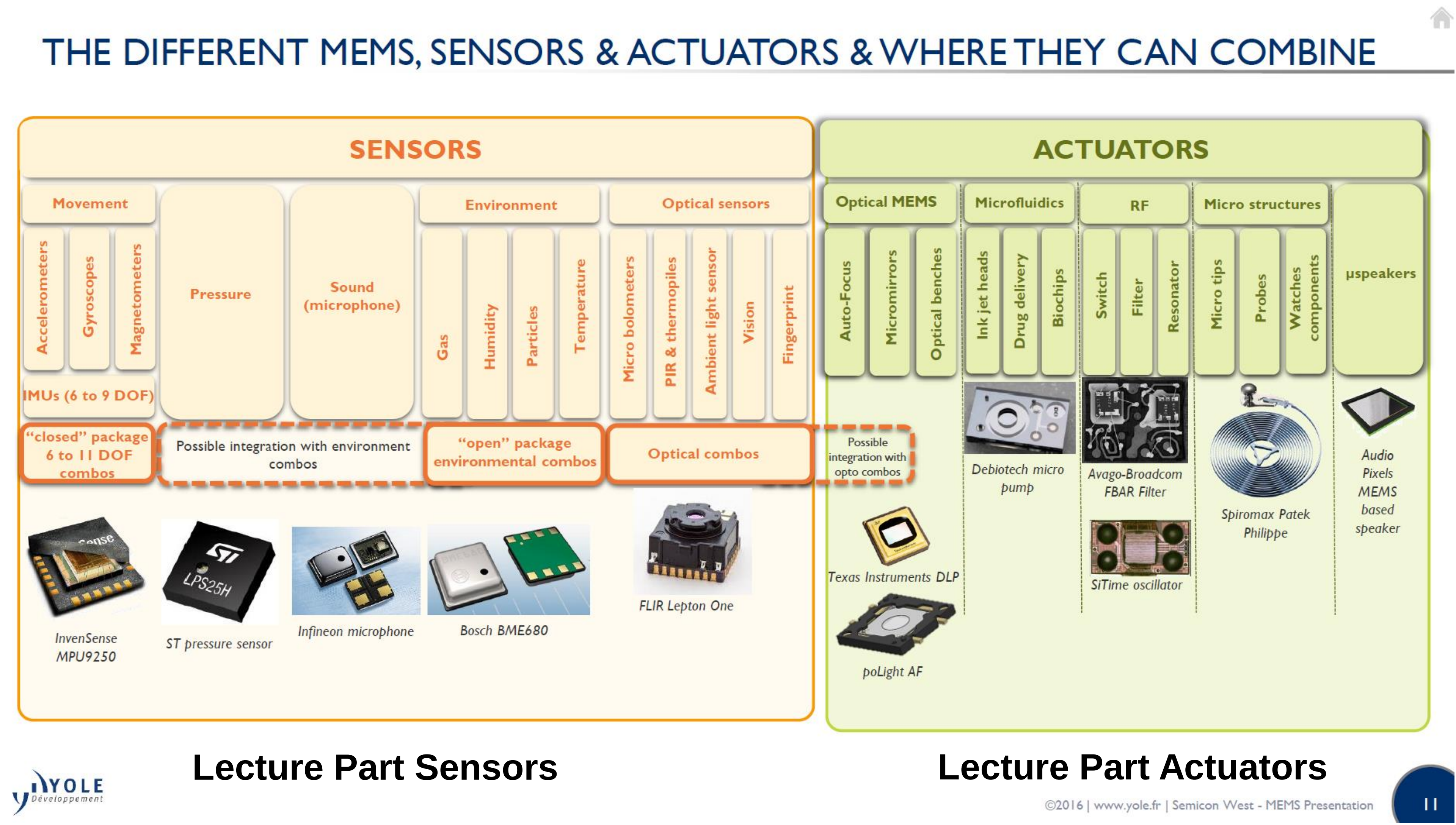
IN 2 WEEKS ON 11 MARCH

- **Hand-In Answers to Questions on Industrial Seminar 1 – Safran**
- **YOUR Presentation (Graded - Requires some homework)**
- **SIGN UP: Link**

Announcement: Remember Presentations (doodle sign-up)

- **5 min presentation by Team of 2 students** on an Advanced MEMS Device
- Requires homework during these first weeks
- Content:
  - Historic and status (of the MEMS device only)
  - Operation principle
  - MEMS Implementation
  - Characteristics (via data sheet or scientific/technical papers)
  - Packaging & system integration
  - Products and current applications
- 6 slides (1 per bullet point): Use the template available on Moodle
- Selection of your device by team of 2 **students** via this google drive link: Link topics selection
- **Date of Presentation: 11th of March (in 2 Weeks)**
- **SIGN UP! X / 16 have signed up (as of 25.02),** *you can join a single person registered by asking if she/he would like to team up.*

MEMS Sensors and Actuators



THE DIFFERENT MEMS, SENSORS & ACTUATORS & WHERE THEY CAN COMBINE

SENSORS

- Movement
  - Accelerometers
  - Gyroscopes
  - Magnetometers
  - IMUs (6 to 9 DOF)
- Pressure
- Sound (microphone)
- Environment
  - Gas
  - Humidity
  - Particles
  - Temperature
- Optical sensors
  - Micro bolometers
  - PIR & thermopiles
  - Ambient light sensor
  - Vision
  - Fingerprint

"closed" package 6 to 11 DOF combos

Possible integration with environment combos

"open" package environmental combos

Optical combos

InvenSense MPU9250

ST pressure sensor

Infineon microphone

Bosch BME680

FLIR Lepton One

ACTUATORS

- Optical MEMS
  - Auto-Focus
  - Micromirrors
  - Optical benches
- Microfluidics
  - Ink jet heads
  - Drug delivery
  - Biochips
- RF
  - Switch
  - Filter
  - Resonator
- Micro structures
  - Micro tips
  - Probes
  - Watches components
- µspeakers

Possible integration with opto combos

Texas Instruments DLP

poLight AF

Debiotech micro pump

Avago-Broadcom FBAR Filter

SiTime oscillator

Spiromax Patek Philippe

Audio Pixels MEMS based speaker

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Lecture Part Sensors

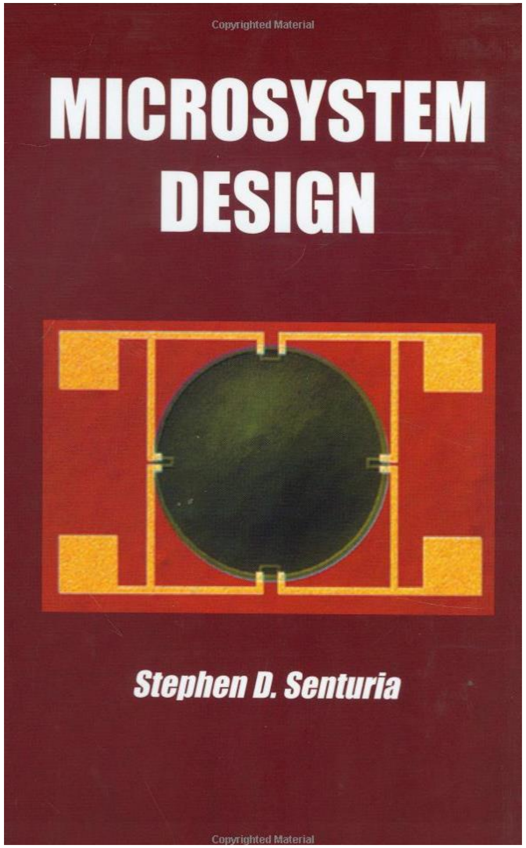
Lecture Part Actuators

LECTURE 2

Sensors – Part 1

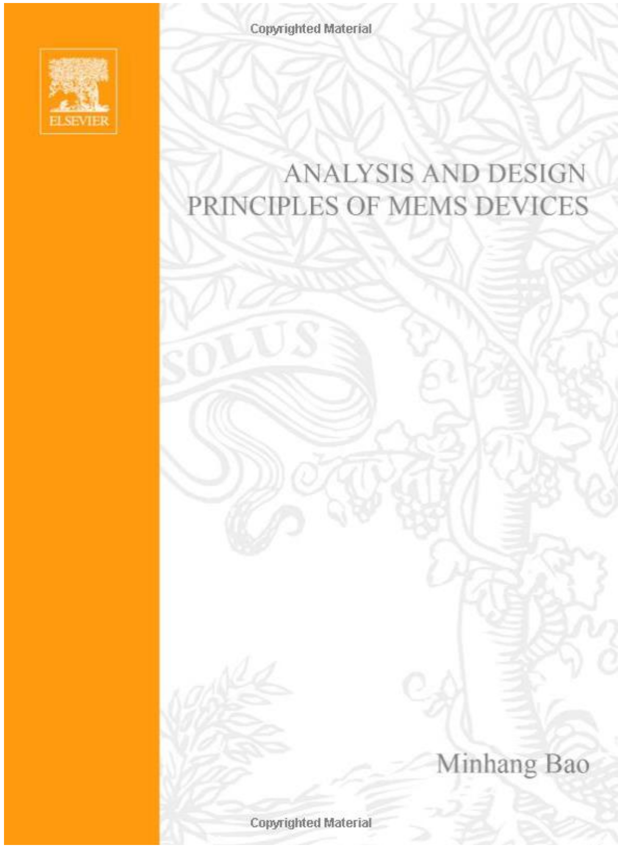
Dr. Danick Briand
Maître d'Enseignement et de Recherche (MER)
MEMS & Printed Microsystems group
EPFL-STI-LMTS

Reference Books



MICROSYSTEM DESIGN

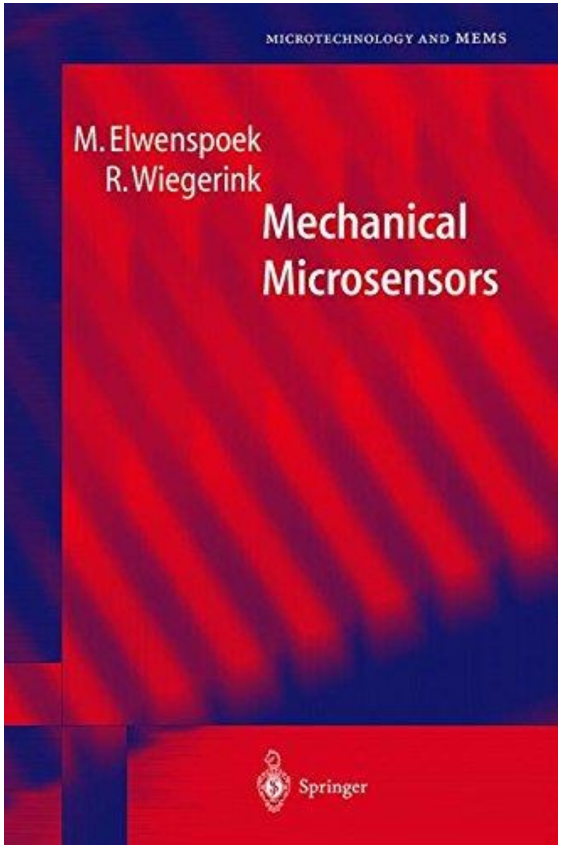
Stephen D. Senturia



ELSEVIER

ANALYSIS AND DESIGN PRINCIPLES OF MEMS DEVICES

Minhang Bao



MICROTECHNOLOGY AND MEMS

M. Elwenspoek
R. Wiegerink

Mechanical Microsensors

Springer

also: EPFL MICRO-330: Sensors

What is a Transducer?

What is a Sensor ?

TRANSDUCTION PRINCIPLES

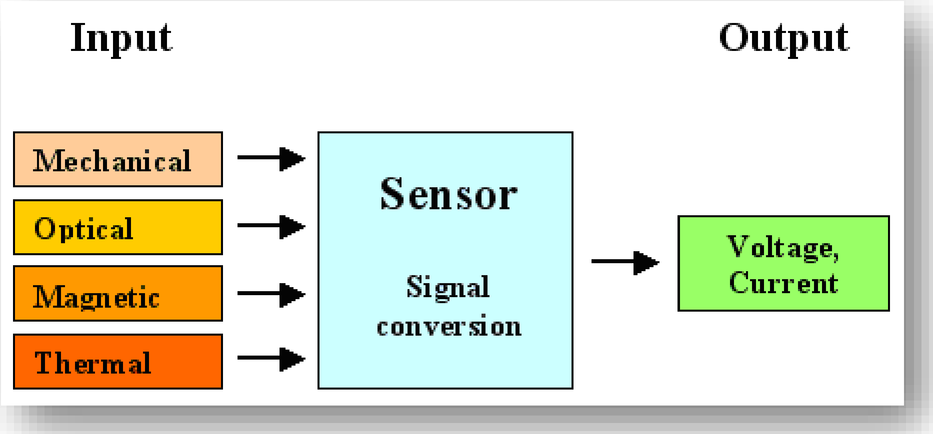
See pre-recorded lecture of last week on the moodle

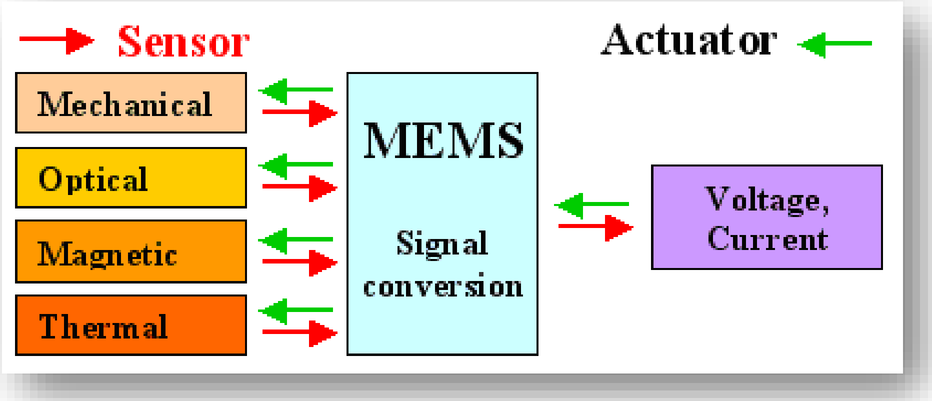
Definition of a transducer in MEMS

A transducer is a device, usually electrical, electronic, or electro-mechanical, that converts one type of energy to another for the purpose of measurement or information transfer. Most transducers are either sensors or actuators. In a broader sense, a transducer is sometimes defined as any device that senses or converts a signal from one form to another .

(www.Wikipedia.com)

Sensors and actuators





Definition of a sensor

A **device that responds to a physical or (bio)chemical stimulus**

(such as ions, molecules, gases, heat, light, sound, pressure,

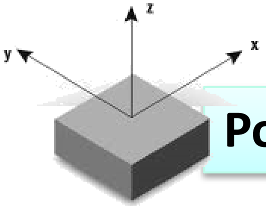
magnetism, or a particular motion) and transmits a resulting signal

MEMS Sensors - what can be measured ?

Over the past several decades MEMS researchers and developers have demonstrated an extremely large number of microsensors for almost every possible sensing modality

Temperature

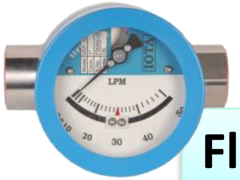
Pressure



Position

Magnetic fields

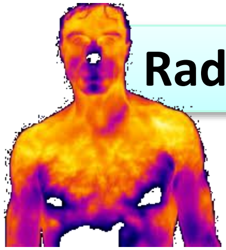
Humidity



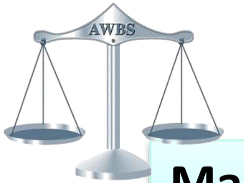
Flow

Soundwaves

Surface stress



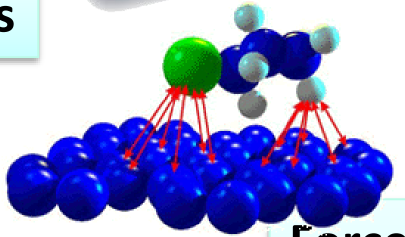
Radiation (IR)



Mass

Inertial forces

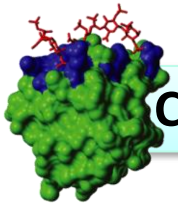
(acceleration – angular rate)



Forces

Magnetic
Van der Waals
Coulomb
…

Proximity



Chemical Species

Etc …

Overview and Goals of this Lecture

- **Sensors - Review of terminology and MEMS advantages**

- **Focus on 2 Sensing Mechanisms based on detection of mechanical movement at the microscale: Piezoresistive readout and Capacitive readout**

- **Discussion of different types of Advanced MEMS Sensors**

- **Related industrial Seminar 1: MEMS Accelerometers SAFRAN-COLIBRYS**
- **Related industrial Seminar 2: MEMS Sensors SENSIRION**

- **Related content discussed later in the course**
  - **Microphones → Lecture 26 March**
  - **Resonant Sensors → Lecture 9 April**
  - **Gas Sensors → Lecture 30 April**

- **Not discussed in these Lectures:**
  - **Other Sensing Mechanisms**

Sensors Part I: Lecture content

- **Why MEMS Sensors? Why Sensing *within* Microsystems?**

- **MEMS Sensing Techniques**
  - **Overview of MEMS Sensor Types and Sensing Techniques**
  - **Terminology: Accuracy, Precision, Repeatability and Reproducibilty, Stability**
  - **Sensing in MEMS: General Principle & Capacitive + Piezoresistive**

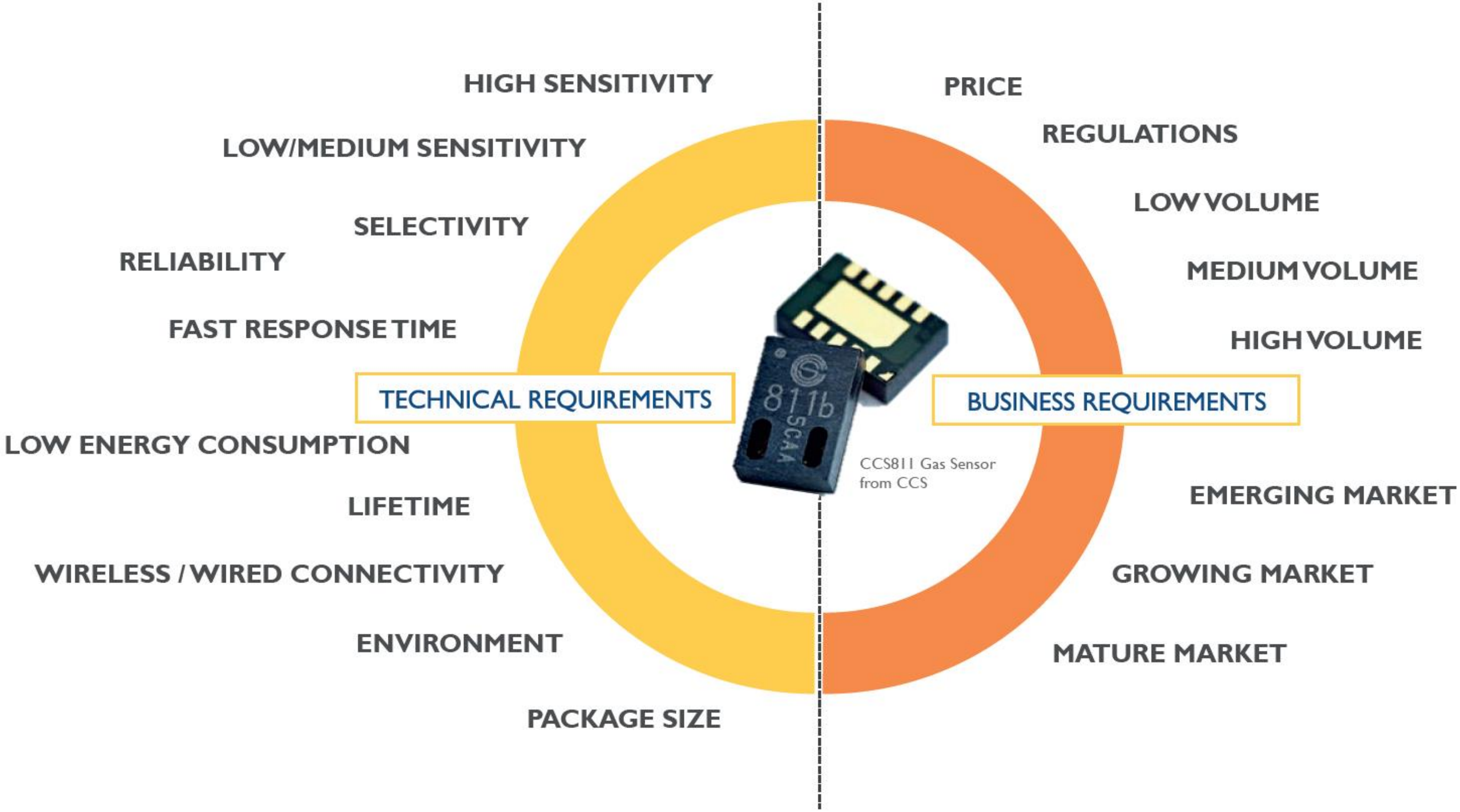
- **Piezoresistive Sensing**
  - **Piezoresistivity**
  - **Examples of Piezoresistive MEMS Sensors**

- **Piezoresistive MEMS Pressure Sensors**
  - **Working Principle**
  - **Applications, Market Overview**
  - **Fabrication Technologies**

- **Piezoresistive AFM Cantilever (Example)**
- **Membrane-type Surface Stress Sensor (Example)**

Sensors: Why MEMS?

Technical and Economical Requirements



HIGH SENSITIVITY

LOW/MEDIUM SENSITIVITY

SELECTIVITY

RELIABILITY

FAST RESPONSE TIME

TECHNICAL REQUIREMENTS

LOW ENERGY CONSUMPTION

LIFETIME

WIRELESS / WIRED CONNECTIVITY

ENVIRONMENT

PACKAGE SIZE

PRICE

REGULATIONS

LOW VOLUME

MEDIUM VOLUME

HIGH VOLUME

BUSINESS REQUIREMENTS

EMERGING MARKET

GROWING MARKET

MATURE MARKET

CCS811 Gas Sensor from CCS

(Yole Développement, February 2016)

Sensors: Why MEMS?

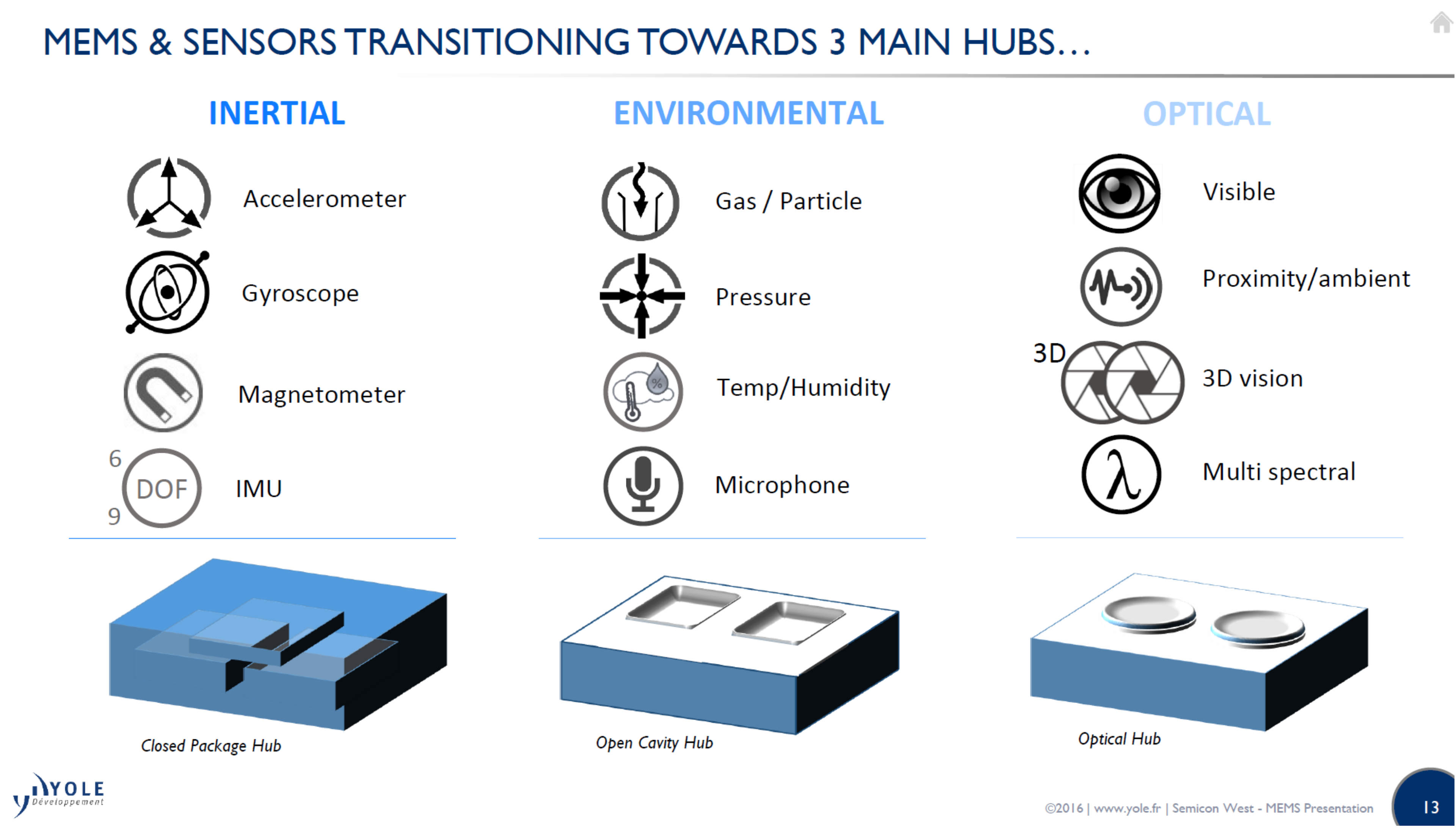
Sensors: The MEMS Advantage

1. **Size**
2. **Cost Advantage in Mass Production**
3. **Low Power Consumption (e.g. Mobile)**
4. **Performance (sometimes 'good enough')**
5. **Integrated Signal Conditioning**
6. **Standard Electrical Interfacing *for* Mass Production**
7. **…**

Examples of Market Drivers

Consumer Electronics
Medical Technologies
Industrial Applications
Internet of Things
Robotics
…

MEMS Sensor Hubs



MEMS & SENSORS TRANSITIONING TOWARDS 3 MAIN HUBS…

INERTIAL

- Accelerometer
- Gyroscope
- Magnetometer
- 6 DOF 9 IMU

Closed Package Hub

ENVIRONMENTAL

- Gas / Particle
- Pressure
- Temp/Humidity
- Microphone

Open Cavity Hub

OPTICAL

- Visible
- Proximity/ambient
- 3D 3D vision
- λ Multi spectral

Optical Hub

YOLE Développement

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MEMS Sensing techniques of common sensors

MEMS Sensor Classification by Sensing Application:

Sensing Application	MEMS component	Sensing technique
Atomic Force Microscope	Cantilevers	Optical, piezoresistive, capacitive, …
Pressure	Membrane (semi-static deflection)	Piezoresistive, capacitive
Microphone	Membrane (dynamic deflection)	Capacitive, piezoresistive
Accelerometer	Proof mass (static or vibrating)	Capacitive, piezoresistive
Gyroscope	Proof mass (vibrating)	capacitive
(Magnetometer)	(integrated electronics, typically combined with motion sensors)	Hall effect, magnetoresistive
Flow sensors	Membrane or cantilevers (pressure or cooling of heated element)	Piezoresistive, thermal
IR Sensors / Bolometers	Membranes or cantilevers (displacement due to ΔT)	Piezoresistive, capacitive, thermopiles
Frequency (for time base)	Vibrating frames, tines, or bulk	Piezoelectric, piezoresistive

MEMS Sensing techniques of common sensors

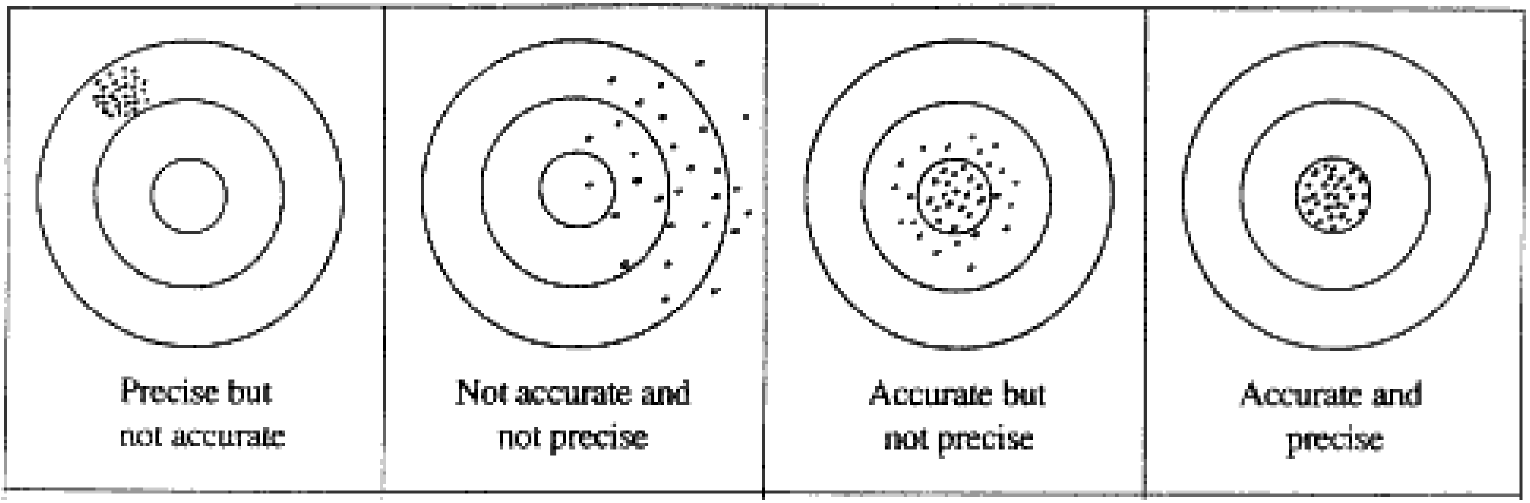
MEMS Sensor Classification by Sensor Type:

Sensor type	**Sensing principles**	**Applications**
Mechanical	Strain gauge, piezoresistance	Force, pressure, stress
Thermal	Resistor, thermocouple, semiconductors, thermopile	Temperature, IR radiation, amperometer, flow
Capacitive	Capacitance	Proximity, position, pressure, acceleration, angular rates, microphone
Inductive	LVDT with conditioner	Proximity, displacement
Magnetic	Hall effect, magnetoresistance, magnetostriction	Compass, Magnetometer
Piezoelectric	Piezoelectric effect	Acceleration, Microphone, pyroelectric sensors (IR, T)
Resonant sensors	Oscillators with interfaces	Force, pressure, temperature, micro-balance, gyroscopes, flow, …
Chemical	Catalysis, conducstance, electrochemistry	Biomedicals, MicroTAS, …
Optical	Photodiode, reflectance, …	Encoders, integrated optics

Sensor Specs

- accuracy
- precision
  - repeatability
  - reproducibility
- stability

Sensor Specification: Accuracy and Precision



Precision

"The ability of a measurement to be consistently reproduced."

Repeatability

"*minimum* variability in results of a measurement system"

(typically with a restricted set of conditions, e.g. the same operator)

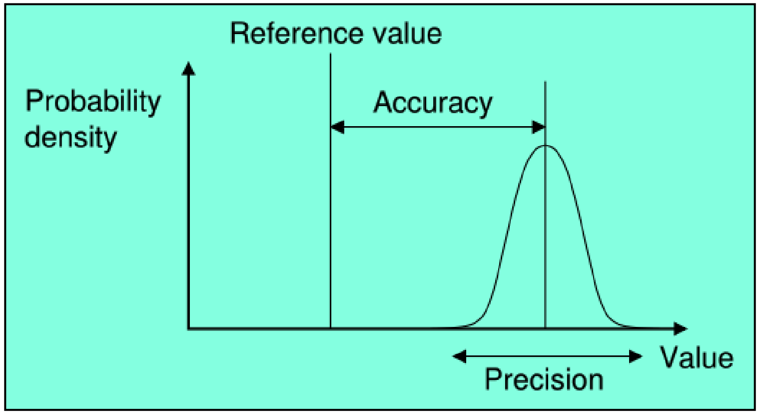
Reproducibility

"*maximum* variability in results of a measurement system"

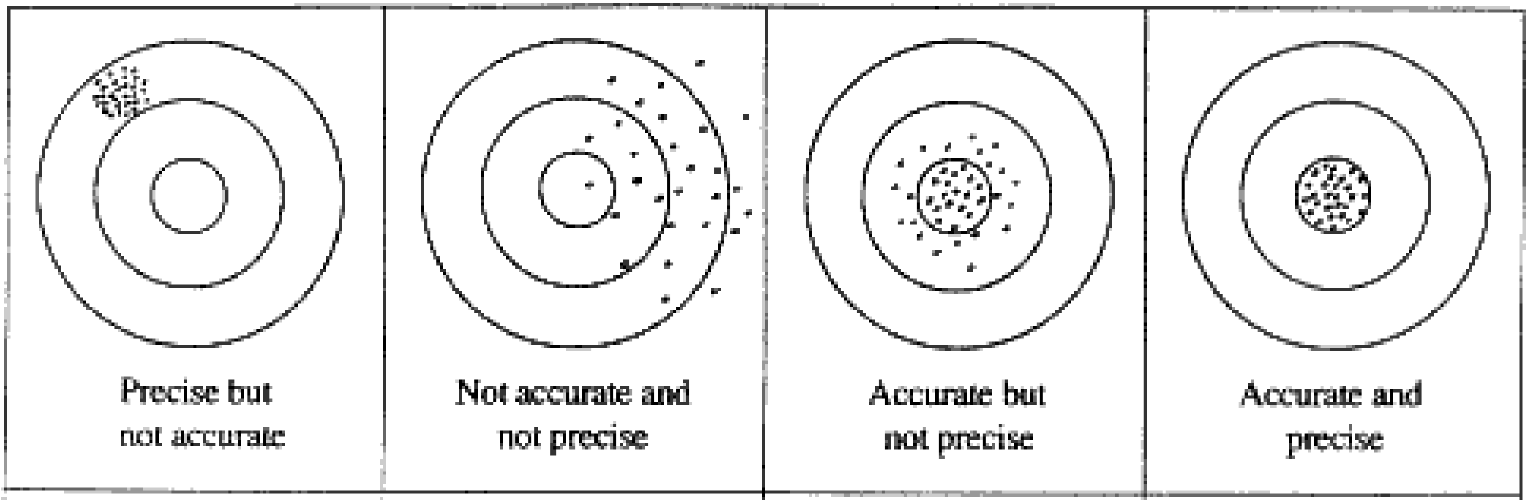
(typically between different operators, e.g.same measurement at different laboratories)

Accuracy (Trueness)

"The ability of a measurement to match the actual (true) value of the quantity being measured."



Sensor Specification: Accuracy and Precision



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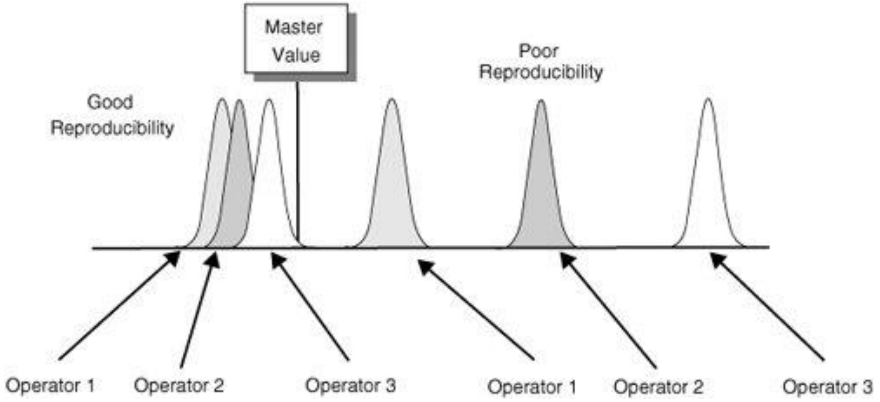
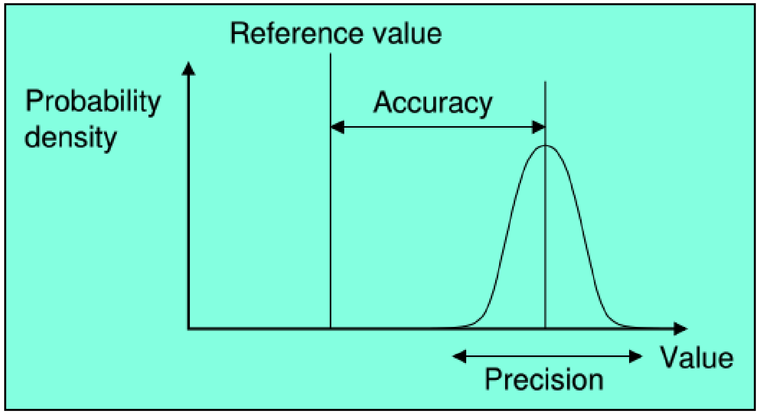
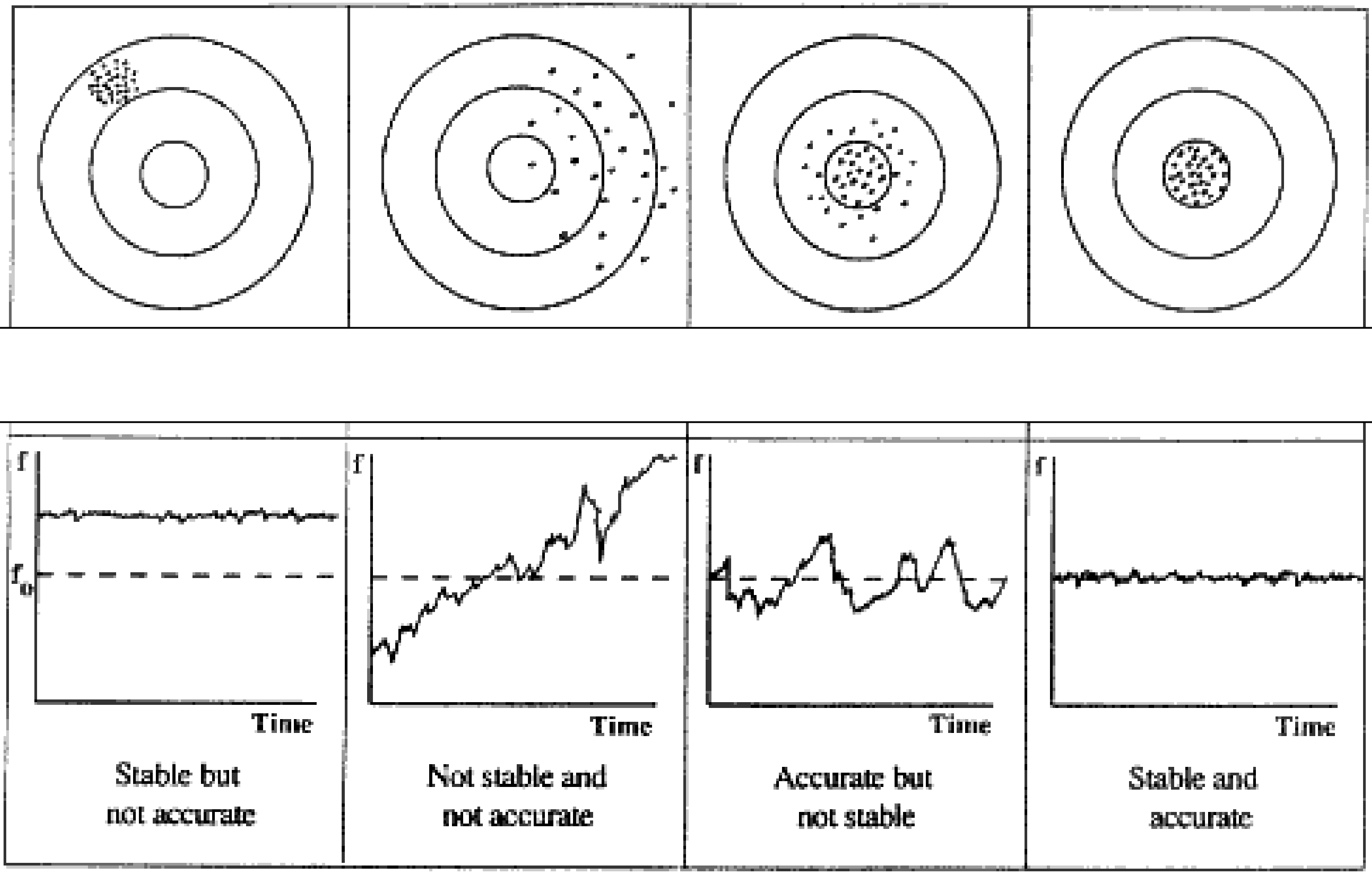




Accuracy and Precision vs. Stability



Stable but not accurate

Not stable and not accurate

Accurate but not stable

Stable and accurate

Stability: Measurement over Time

Sensor Specs

- accuracy
- precision
  - repeatability
  - reproducibility
- stability

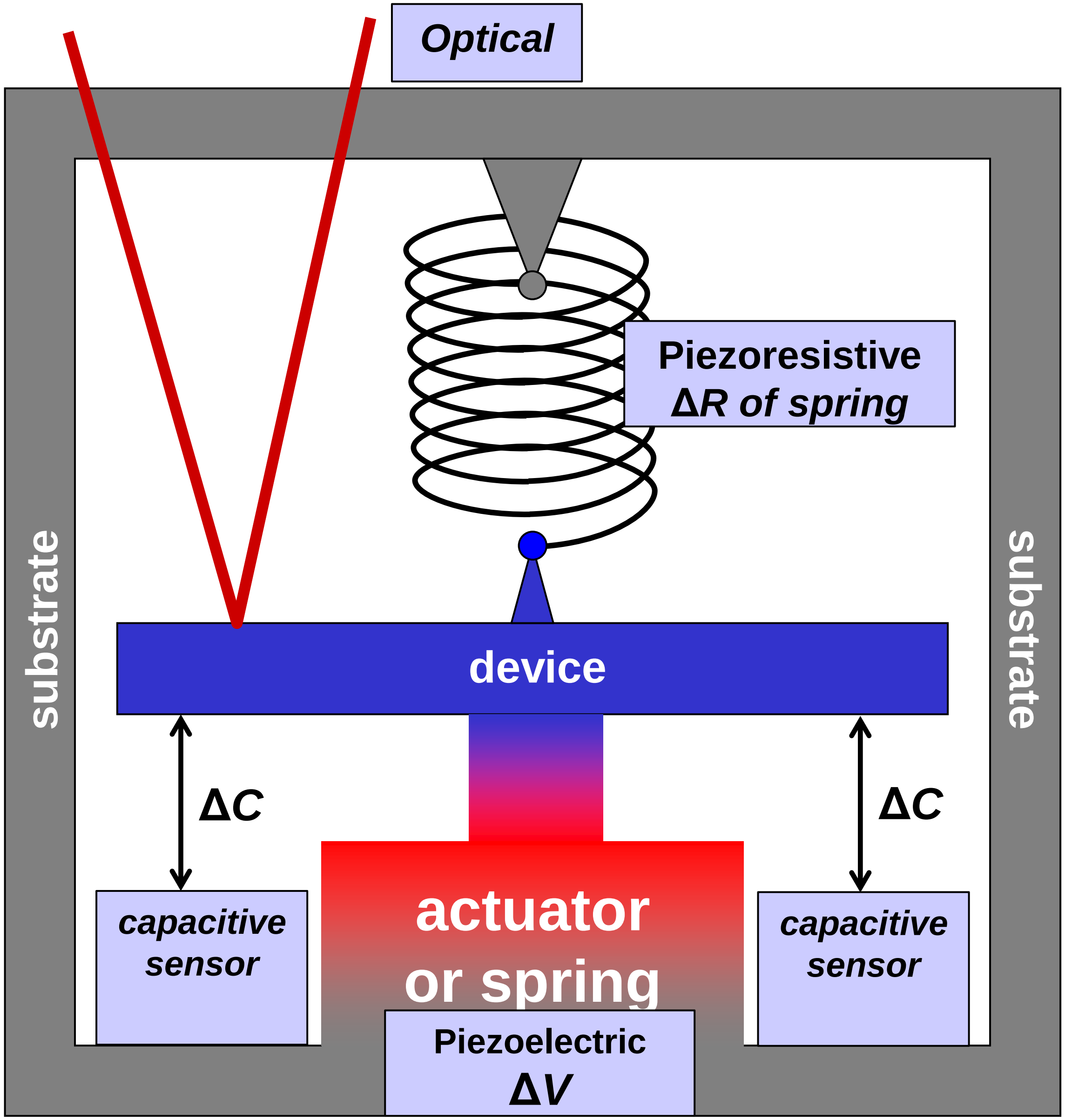
- resolution
- sensitivity
- linearity
- SNR / limit of detection
- threshold
- responsivity
- gain
- specificity / selectivity
- speed (response time / recovery time)
- spectral response
- sales (application: cost, size, weight, power, logistics)
- …

MEMS Actuator & Sensor: General Concept

MEMS Elements

1. Device
2. Actuator (one-way)
3. Restoring force
4. Sensor for position detection

- ➢ enables feedback
- ➢ integrated sensing
  - capacitive
  - piezoresistive

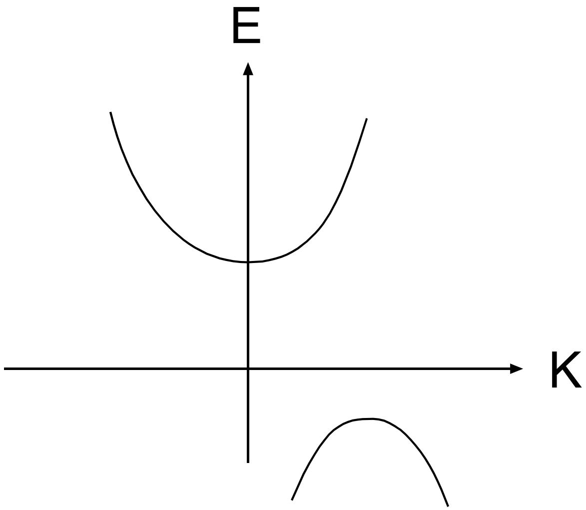


PIEZORESISTIVE SENSING

Electrical Conductivity Change With Stress/Strain

- **Change of electrical conductivity and resistivity as a result of crystal lattice deformation.**
- **Strain causes the shape of energy band curves to change, therefore changing the effective mass, m*. Therefore electrical conductivity σ changes.**

$$m^* = \frac{h^2}{d^2E/dk^2} \qquad \sigma = \frac{q\bar{t}}{m^*}$$



Crystal bandgap structure

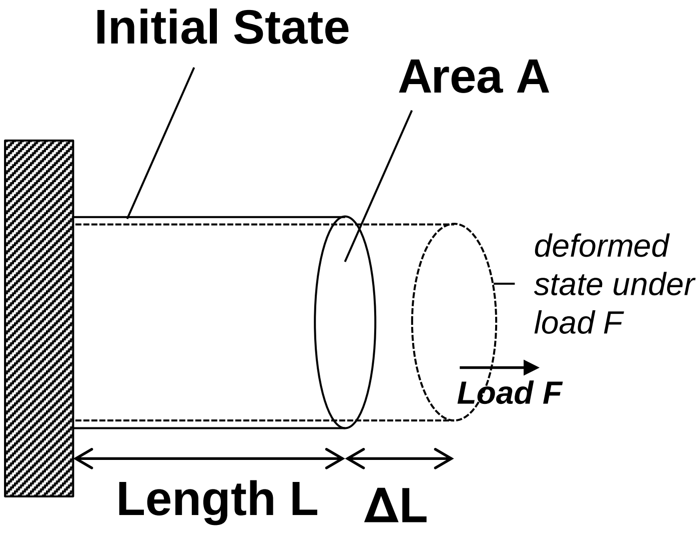
- G is called Gauge Factor of a piezoresistor. It determines the amplification factor between strain and resistance change.

$$\frac{\Delta R}{R} = G \bullet \frac{\Delta L}{L} \qquad G = \frac{\frac{\Delta R}{R}}{\frac{\Delta l}{l}} = \frac{\Delta R}{\varepsilon R}$$

Ref: Chang Liu; MASS UIUC

Piezoresistivity: The Gauge Factor

G = Gauge Factor of a Piezoresistor
= Amplification Factor Between Strain and Resistance Change



Hooke's Law: $\frac{F}{A} = \sigma = \varepsilon E = E\frac{\Delta L}{L}$

Resistance of Cylinder: $R = \frac{\rho L}{A}, cylinder: R = \frac{4L\rho}{\pi d^2}$

$$\mathrm{d}R = \frac{\partial R}{\partial \rho}\mathrm{d}\rho + \frac{\partial R}{\partial L}\mathrm{d}L + \frac{\partial R}{\partial d}\mathrm{d}d$$

$$\frac{\mathrm{d}R}{R} = \frac{\mathrm{d}\rho}{\rho} + \frac{\mathrm{d}L}{L} - 2\frac{\mathrm{d}d}{d}$$

$$Poisson\ Coefficient\ \nu = -\frac{\frac{\mathrm{d}d}{d}}{\frac{\mathrm{d}L}{L}}$$

$$\frac{\mathrm{d}R}{R} = \frac{\mathrm{d}\rho}{\rho} + \frac{\mathrm{d}L}{L}(1 + 2\nu)$$

Piezoresistive Coefficient Π
Youngs Modulus E

$$\Pi\mathrm{E} = \frac{\frac{\mathrm{d}\rho}{\rho}}{\frac{\mathrm{d}L}{L}}$$

$$\frac{\mathrm{d}R}{R} = (\Pi\mathrm{E} + 1 + 2\nu)\frac{\mathrm{d}L}{L}$$

$$\frac{\mathrm{d}R}{R} = G\frac{\mathrm{d}L}{L}$$

Gauge Factor $\mathrm{G} = \Pi\mathrm{E} + 1 + 2\nu$

Piezoresistivity: The Gauge Factor

G = Gauge Factor of a Piezoresistor
= Amplification Factor Between Strain and Resistance Change

ΠE takes into account the change in <u>resistivity</u> only

Dominant in Semiconductors

$1 + 2\nu$ takes into account the change in <u>geometry</u> only

Dominant in Metals (K ≈ 2)

Gauge Factor $G = \Pi E + 1 + 2\nu$

Material	Gauge Factor G
Metal Foil	1 – 5
Crystalline Silicon	80 – 150
Diffused Doped Silicon	10 – 200

Anisotropic Piezoresistivity in Single Crystalline Silicon

Ohm's Law $\vec{E} = \rho\vec{J}$

- E - electric field, three components
- j - current density, three components
- ρ_0 – homogeneous resistivity, unstressed silicon

Ohm's Law under anisotropic stress

$$\vec{E} = [\rho_{unstressed} + \rho_{stress}]\vec{J}$$
$$\vec{E} = \rho_0[1 + \Pi\sigma]\vec{J}$$

$$\begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix} = \rho_0 \begin{bmatrix} j_1 \\ j_2 \\ j_3 \end{bmatrix} + \rho_0 \begin{bmatrix} d_1 & d_6 & d_5 \\ d_6 & d_2 & d_4 \\ d_5 & d_4 & d_3 \end{bmatrix} \begin{bmatrix} j_1 \\ j_2 \\ j_3 \end{bmatrix}$$

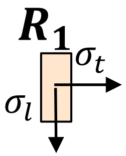
- When mechanical stress is applied, the resistivity changes depending on the stress in different directions and the piezo coefficients

- Simplified tensor by exploiting orthotropic and symmetric silicon material
(3 independent π coefficients)

$$\begin{bmatrix} d_1 \\ d_2 \\ d_3 \\ d_4 \\ d_5 \\ d_6 \end{bmatrix} = \begin{bmatrix} \pi_{11} & \pi_{12} & \pi_{12} & 0 & 0 & 0 \\ \pi_{12} & \pi_{11} & \pi_{12} & 0 & 0 & 0 \\ \pi_{12} & \pi_{12} & \pi_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & \pi_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & \pi_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & \pi_{44} \end{bmatrix} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{yx} \\ \tau_{zx} \\ \tau_{xy} \end{bmatrix}$$

- **For long, narrow resistor on planar structure (t=transversal, l=longitutinal):**

$$\boxed{\frac{\mathbf{d}R}{R} = \pi_l\sigma_l + \pi_t\sigma_t}$$



(any crystal direction)

Equations 18.1 - 18.5 in Senturia: Microsystem Design

Anisotropic Piezoresistivity in Single Crystalline Silicon

- *l_1, m_1, n_1: sets of direction cosines between the **longitudinal** resistor direction and the crystal axis*

- *l_2, m_2, n_2, between the **transverse** direction and the crystal axis*

- *For (100) wafers, along [110] direction, longitudinal direction cosines are $\left(\frac{1}{\sqrt{2}},\frac{1}{\sqrt{2}},0\right)$and the transverse directions cosines are $\left(-\frac{1}{\sqrt{2}},\frac{1}{\sqrt{2}},0\right)$.*

See also Senturia: Microsystem Design

$$\pi_l = \pi_{11} - 2(\pi_{11} - \pi_{12} - \pi_{44})(l_1^2 m_1^2 + l_1^2 n_1^2 + m_1^2 n_1^2)$$

$$\pi_t = \pi_{12} + (\pi_{11} - \pi_{12} - \pi_{44})(l_1^2 l_2^2 + m_1^2 m_2^2 + n_1^2 n_2^2)$$

Piezoresistive Coefficients in Crystalline Silicon

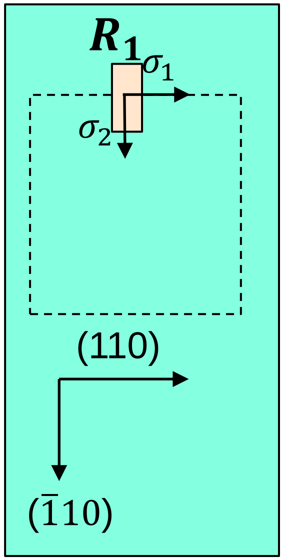
Type	Resistivity	π_{11}	π_{12}	π_{44}
Units	Ωm	$10^{-11}Pa^{-1}$	$10^{-11}Pa^{-1}$	$10^{-11}Pa^{-1}$
n-type	11.7	-102.2	53.4	-13.6
p-type	**7.8**	**6.6**	**-1.1**	**138.1**

p-type: since $\pi_{12} \ll \pi_{44}$ and $\pi_{11} \ll \pi_{44}$,
(and neglecting geometry contribution)

$$\pi_{l,110} = \frac{1}{2}(\pi_{11} + \pi_{12} + \pi_{44}) \approx \frac{1}{2}\pi_{44}$$

$$\pi_{t,110} = \frac{1}{2}(\pi_{11} + \pi_{12} - \pi_{44}) \approx -\frac{1}{2}\pi_{44}$$

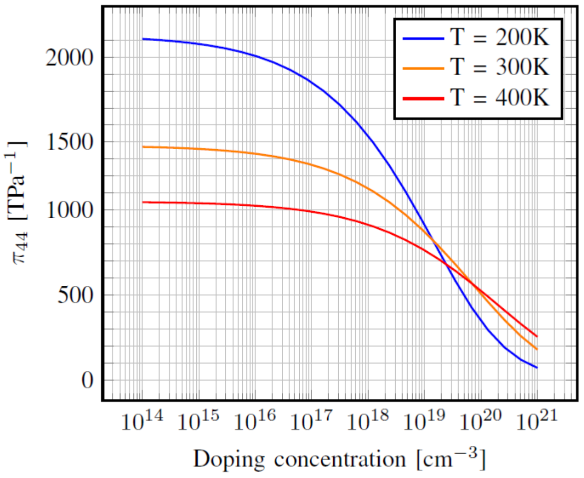
$$\left.\frac{\boldsymbol{dR}}{\boldsymbol{R}}\right|_{(110)} = \boldsymbol{\pi_l \sigma_l + \pi_t \sigma_t \approx \frac{1}{2}\pi_{44}(\sigma_2 - \sigma_1)}$$

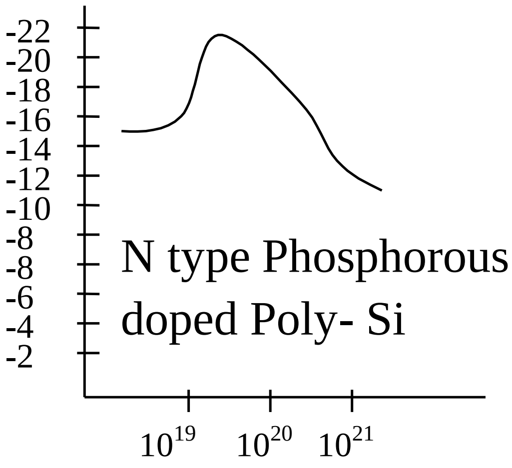


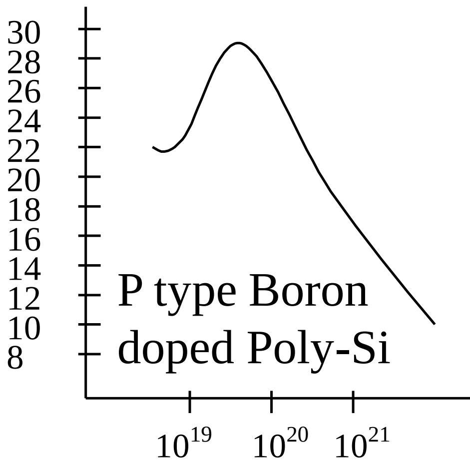
Single and Poly Crystal Silicon Gauge Factors

- **Singly crystal Si, the piezoresistive coefficient smaller for higher doping**
- But almost temperature independent and higher linearity

- **In PolySi, the Gauge factor is isotropic** (random orientations of microcrystalline grains)
- It is a function of doping type and doping concentration.



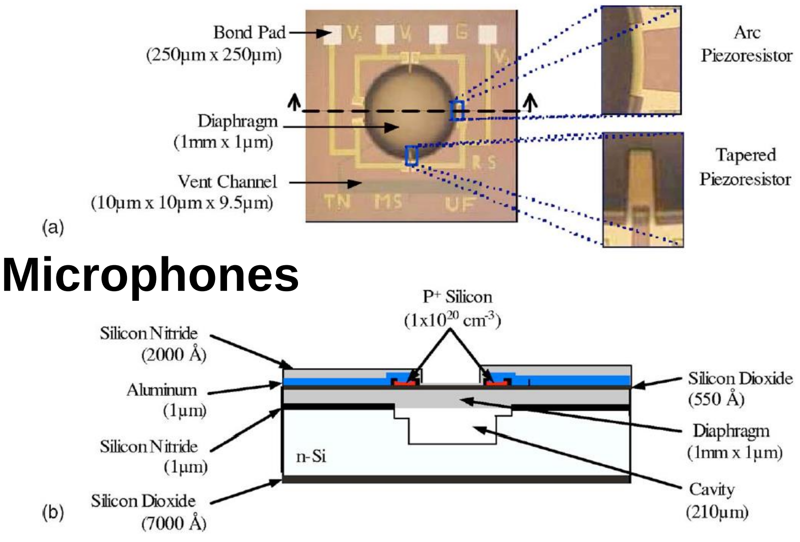




- Silicon piezoresistors easily fabricated with controlled performance specifications using precise ion implantation and diffusion
- Piezoresistive coefficients much higher in single crystal silicon

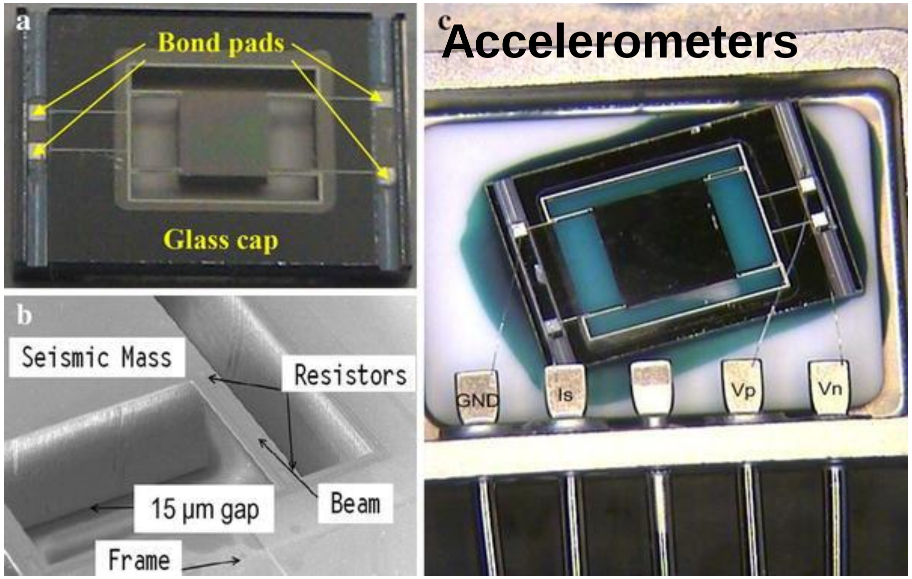
Ref: Chang Liu; MASS UIUC

Examples of Piezoresistive MEMS Sensors



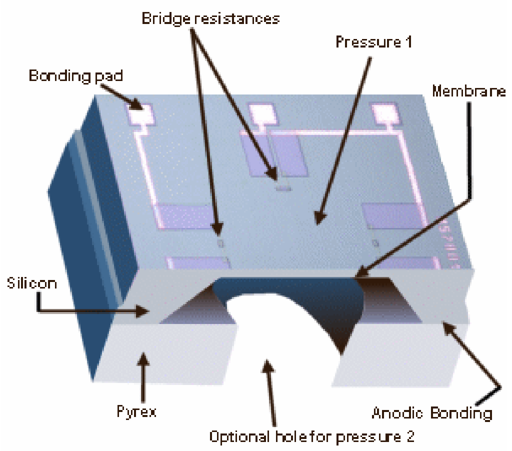
Microphones

Dieme, Boasman, Nishida, Sources of excess noise in silicon piezoresistive microphones 2710 J. Acoust. Soc. Am. 119 5, May 2006



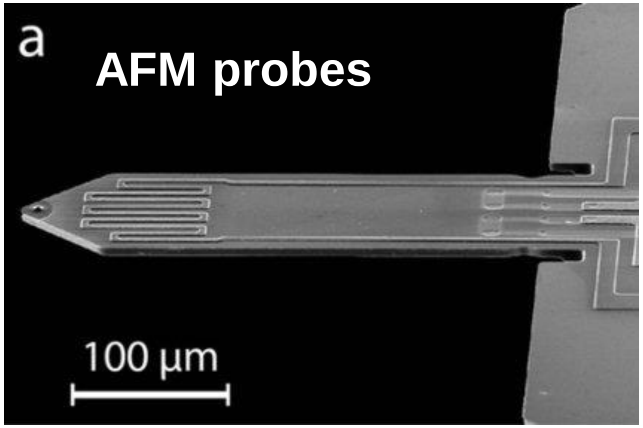
Accelerometers

Roy & Bhattacharryya, Microsystem Technologies, 2015, Volume 21, Issue 1, pp 55–63 Design, fabrication and characterization of high performance SOI MEMS piezoresistive accelerometers



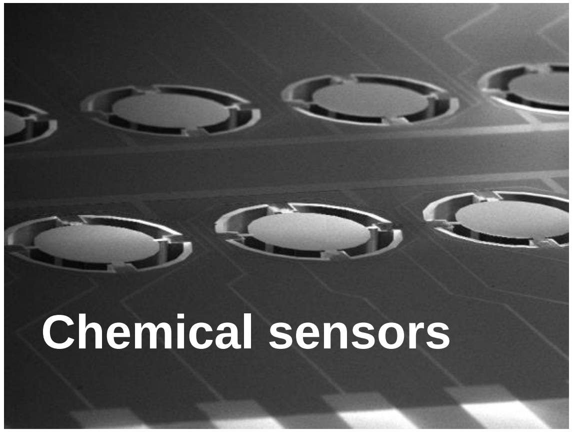
Pressure

TE Connectivity



AFM probes

http://www.sclsensortech.com/

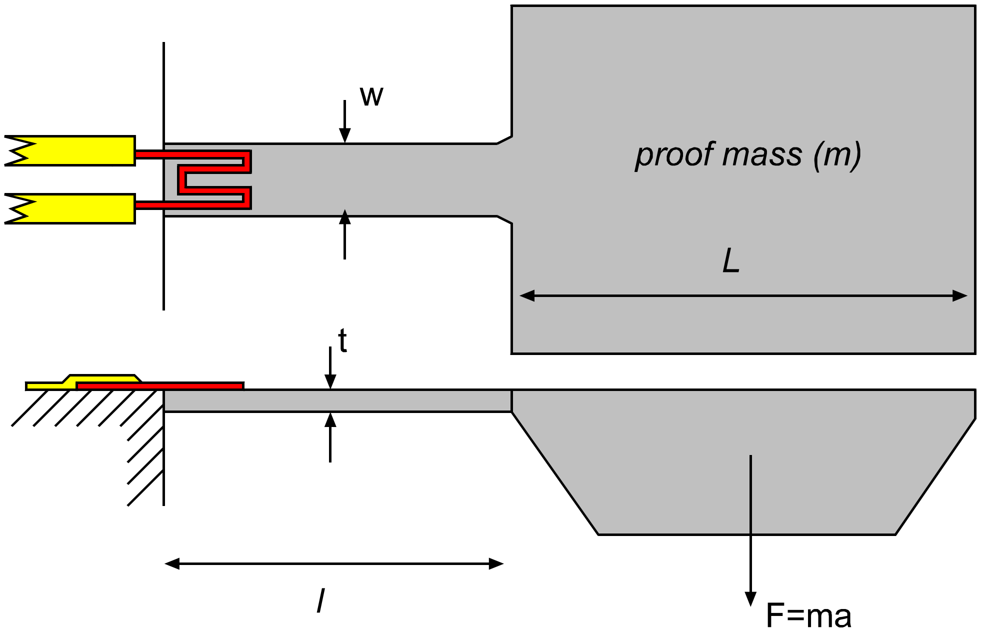


Chemical sensors

MSS Alliance http://www.nims.go.jp/eng/news/press/2015/10/201510130.html

Piezoresistive Si accelerometer

- **Acceleration induced force F, F = ma**
- **The force induces stress at the fixed end of the cantilever beam**
- **The stress is detected in resistance**



<u>Assumptions for modeling</u>

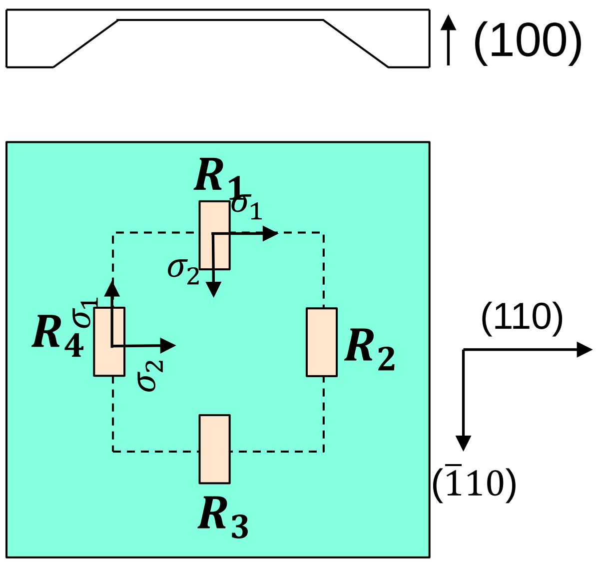
- assume entire resistance is concentrated at the anchor;
- for moment of inertia at the end, ignore the thickness of the resistor.
- Assume the stress on the resistor is the maximum value.
- The proof mass is rigid. It does not bend because of the significant thickness and width.

Ref: Chang Liu; MASS UIU

Working Principle

PIEZORESISTIVE MEMS PRESSURE SENSORS

Differential Readout with Wheatstone Bridge



4 Piezoresistors in Wheatstone Bridge Configuration
2 parallel, and 2 perpendicular to membrane edges
allow for differential readout (p-doped, along <110>-axis):

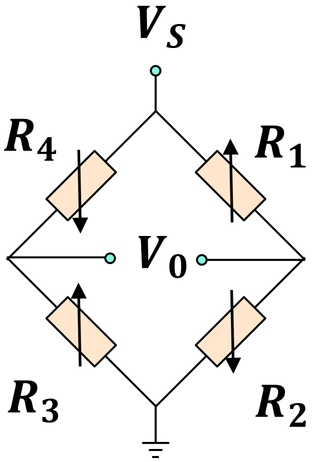
$$\left(\frac{\Delta R}{R_0}\right)_1 = \left(\frac{\Delta R}{R_0}\right)_3 = \pi_l\sigma_l + \pi_t\sigma_t = \frac{1}{2}\pi_{44}(\sigma_2 - \sigma_1)$$

$$\left(\frac{\Delta R}{R_0}\right)_2 = \left(\frac{\Delta R}{R_0}\right)_4 = \pi_l\sigma_l + \pi_t\sigma_t = \frac{1}{2}\pi_{44}(\sigma_1 - \sigma_2)$$

$$\left(\frac{\Delta R}{R_0}\right)_{1,3} = -\left(\frac{\Delta R}{R_0}\right)_{2,4}$$

Differential Readout

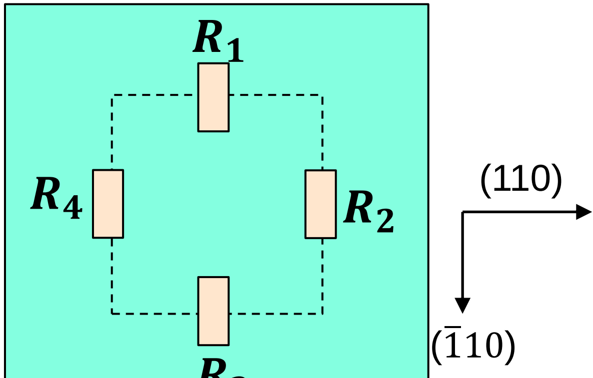
Variations common to all Resistors (e.g. Temperature) are cancelled out!

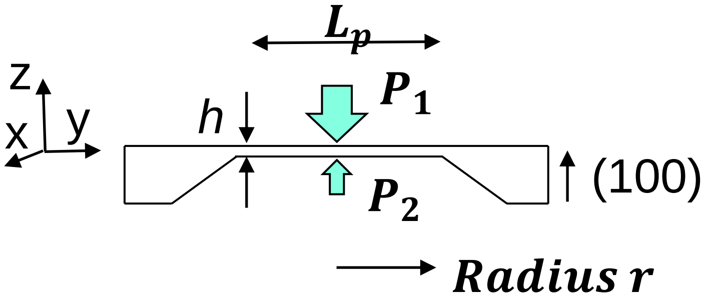


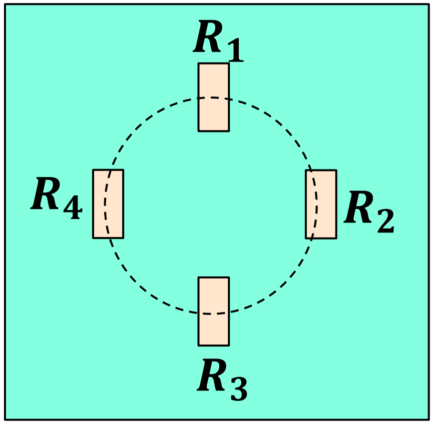
$$V_0 = i_{right}R_2 - i_{left}R_3 = \frac{V_S}{2R_0}\left[R_0\left(1+\left(\frac{\Delta R}{R_0}\right)_2\right) - R_0\left(1+\left(\frac{\Delta R}{R_0}\right)_3\right)\right]$$

$$\boxed{V_0 = \frac{V_S}{2}2\left(\frac{\Delta R}{R_0}\right)_2 = \frac{V_S}{2}\pi_{44}(\sigma_1 - \sigma_2)}$$

Deformation of a Shell







- A membrane of thickness h under pressure difference $\Delta P = P_2 - P_1$ is deformed. For a square membrane a solution can be approximated: (e.g. Timoshenko, Theory of plates and shells).

$$\frac{\partial^4 w}{\partial x^4} + 2\frac{\partial^4 w}{\partial x^4 \partial y^4} + \frac{\partial^4 w}{\partial y^4} = \frac{\Delta P}{D} \qquad D = \frac{Eh^2}{12(1-\nu^2)}$$

stress: $$\sigma_x = \frac{Ez}{1-\nu^2}\left(\frac{\partial^2 w}{\partial x^2} + \nu\frac{\partial^2 w}{\partial y^2}\right) \qquad \sigma_y = \frac{Ez}{1-\nu^2}\left(\frac{\partial^2 w}{\partial x^2} + \nu\frac{\partial^2 w}{\partial y^2}\right)$$

$$\boxed{V_0 \approx \frac{V_S}{2}\pi_{44}\Delta P\frac{L_p^2}{5h^2}}$$

approximation

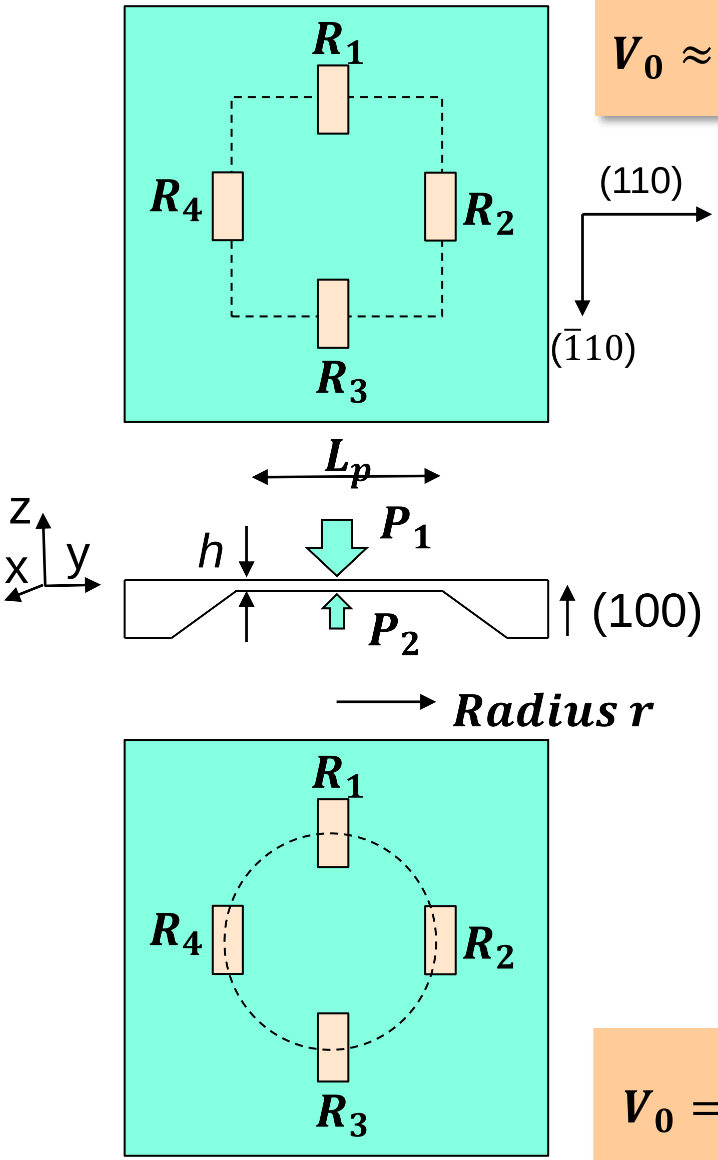
- Equivalently, for circular membrane, an analytical solution can be derived:

$$\boxed{V_0 = \frac{V_S}{2}\pi_{44}\Delta P\frac{3r^2}{4h^2}(1-\nu)}$$

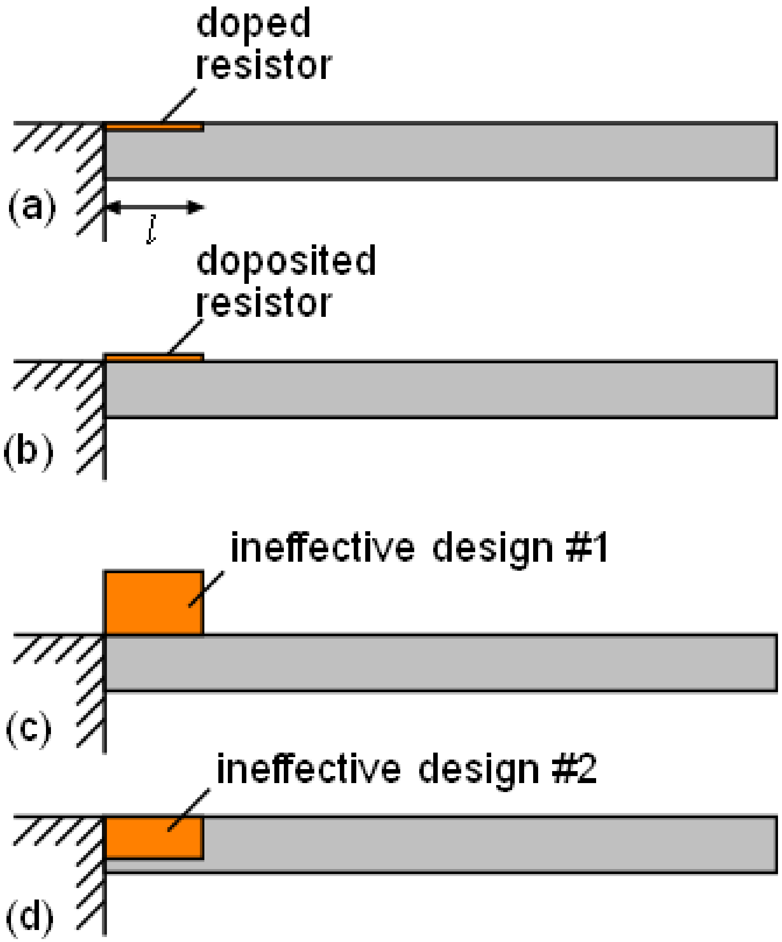
analytical solution

- In order to achieve maximum sensitivity, a **thin** and **large** membrane is needed.

Effective Piezo-Resistor Placement



$$V_0 \approx \frac{V_S}{2}\pi_{44}\Delta P\frac{L_p^2}{5h^2}$$

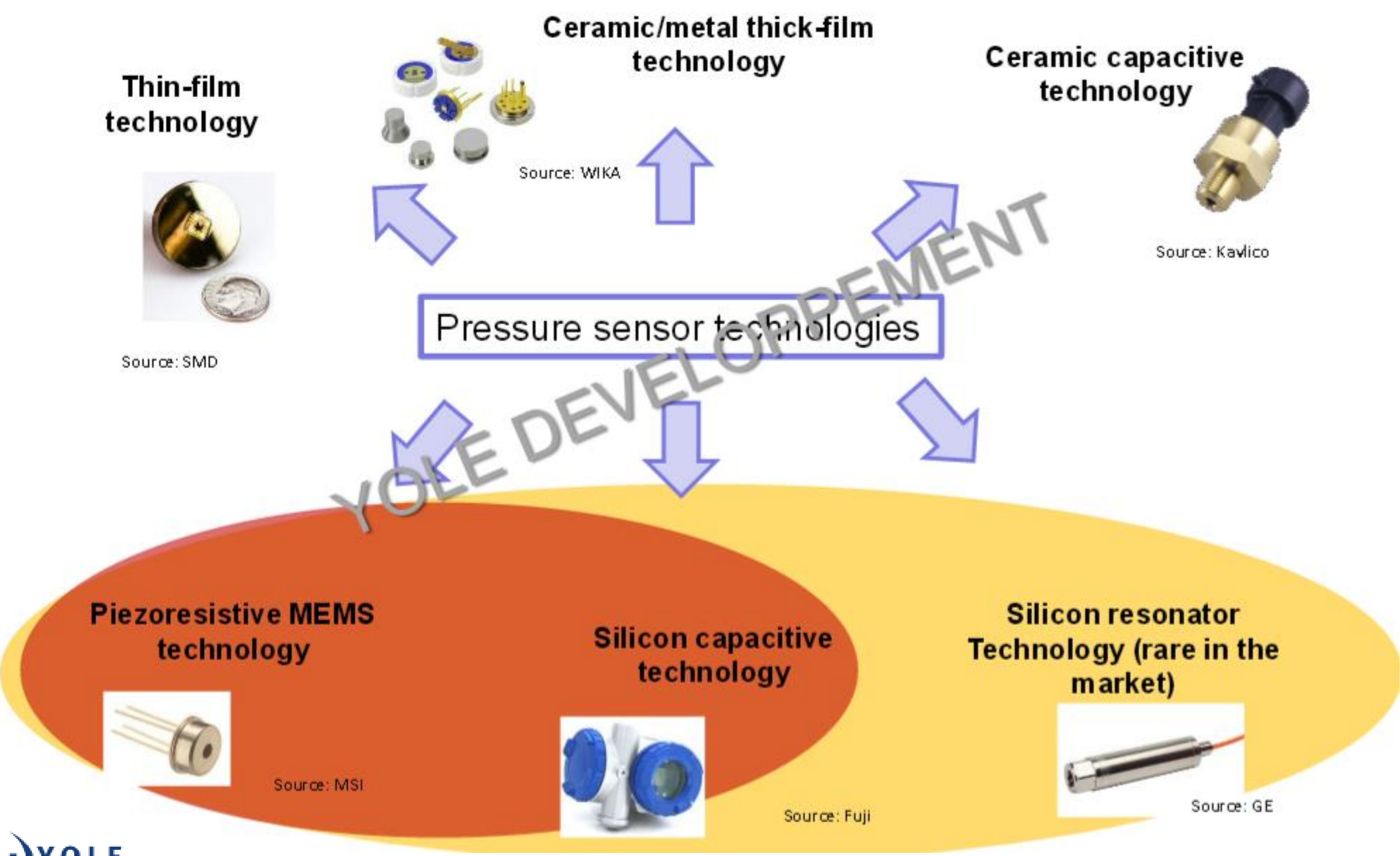


$$V_0 = \frac{V_S}{2}\pi_{44}\Delta P\frac{3r^2}{4h^2}(1-\nu)$$

Applications, Market Overview and Product Examples

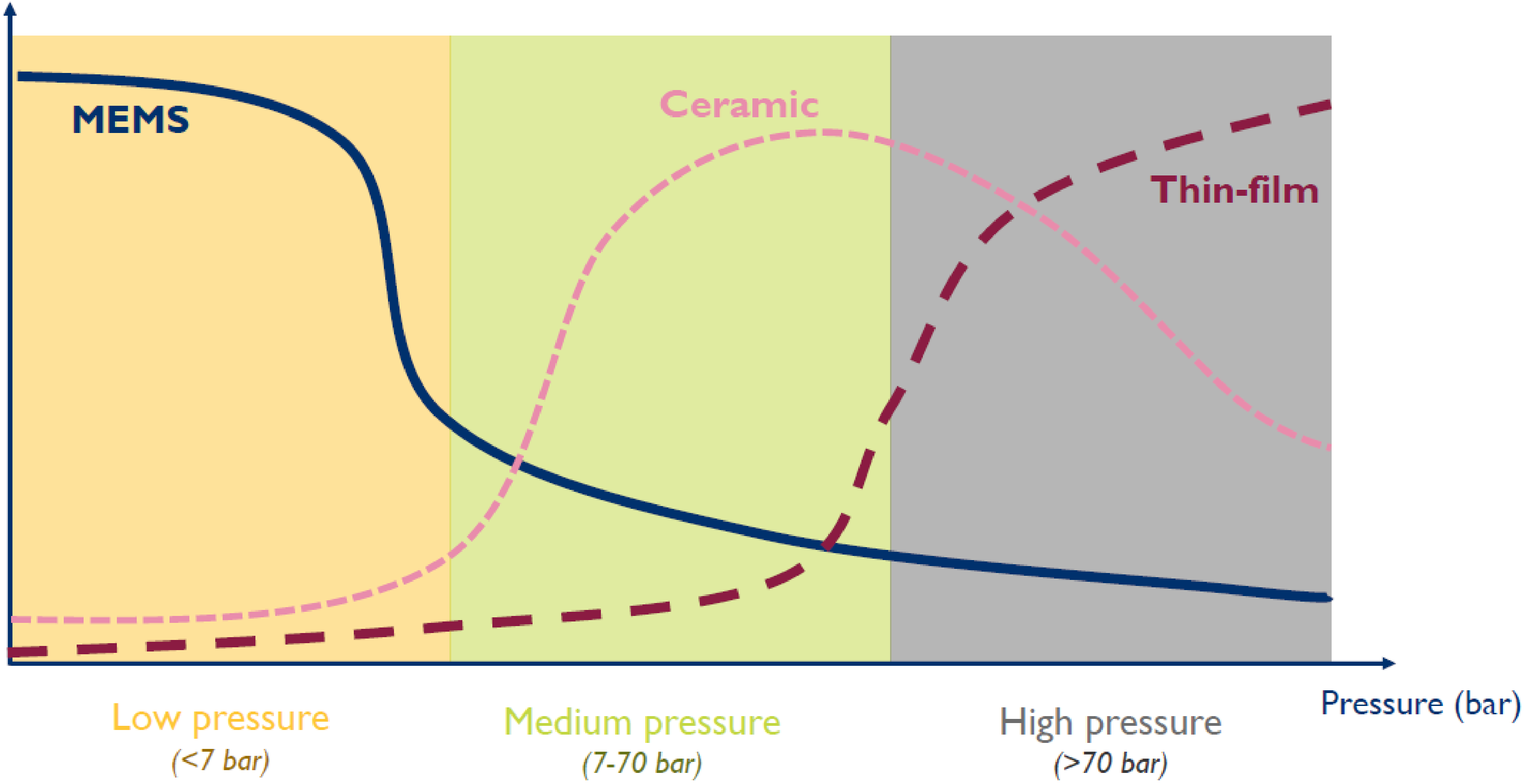
PIEZORESISTIVE MEMS PRESSURE SENSORS

MEMS Pressure sensor technologies



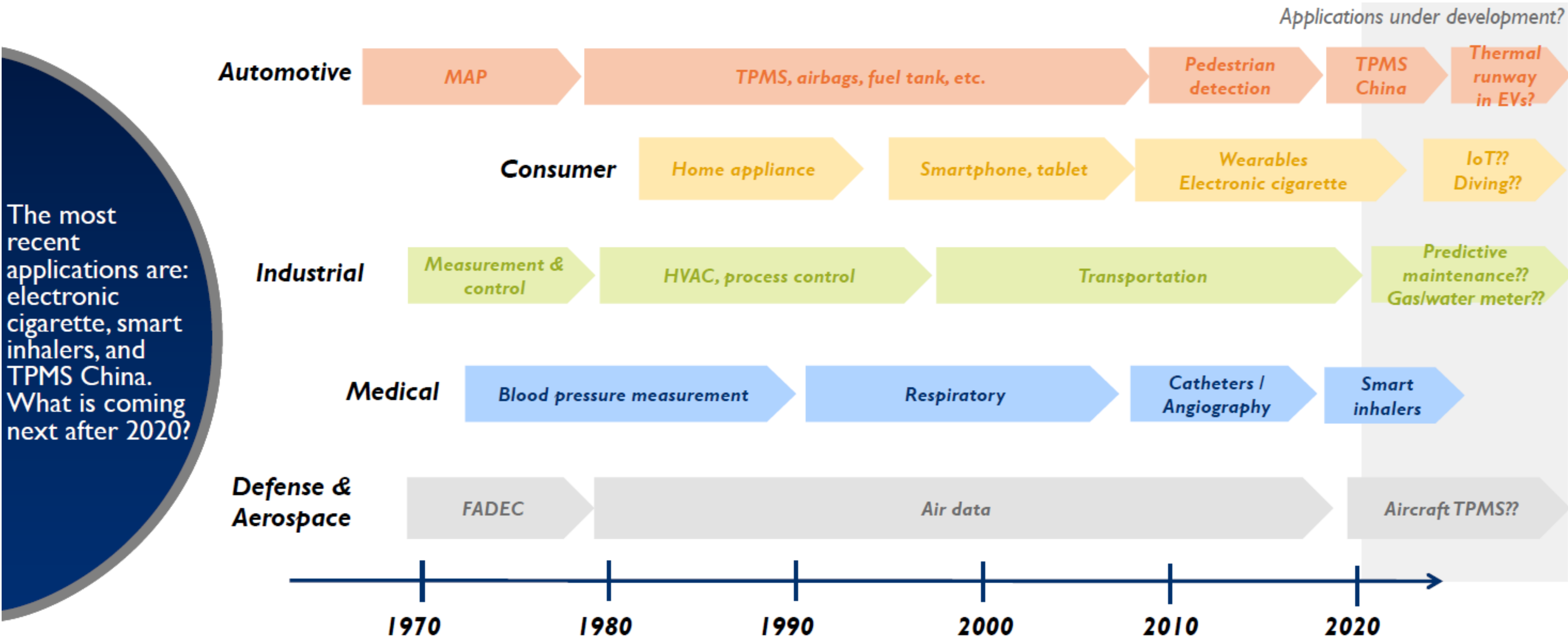
MEMS Pressure sensor technologies

MEMS are better suited for low pressure and some medium pressure applications (<30-50 bar)



MEMS Pressure Sensor Applications

MEMS Pressure Sensor Applications

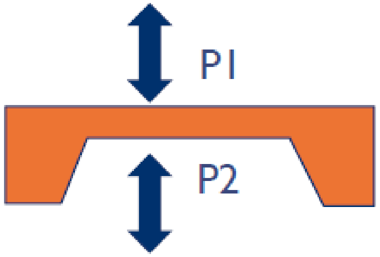


The most recent applications are: electronic cigarette, smart inhalers, and TPMS China. What is coming next after 2020?

MAP: Manufold absolute pressure
HVAC: Heating ventilation air conditioning
TPMS: Tire pressure monitoring
FADEC: Full authority digital engine controls (FADEC) is designed for pressure systems to provide extremely precise and stable pressure measurements over several years.

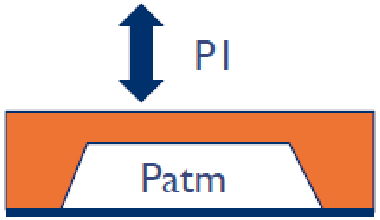
MEMS Pressure Sensor Types

Differential:



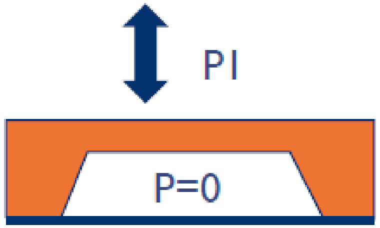
- Measure the difference between two pressure points (P1 and P2)
- Widely used for flow measurement

Gauge:



- A special type of differential measurement: one side of the diaphragm has built-in atmospheric pressure as a reference

Absolute pressure sensor:



- The reference pressure is 0 bar
- This is the most common pressure sensor type

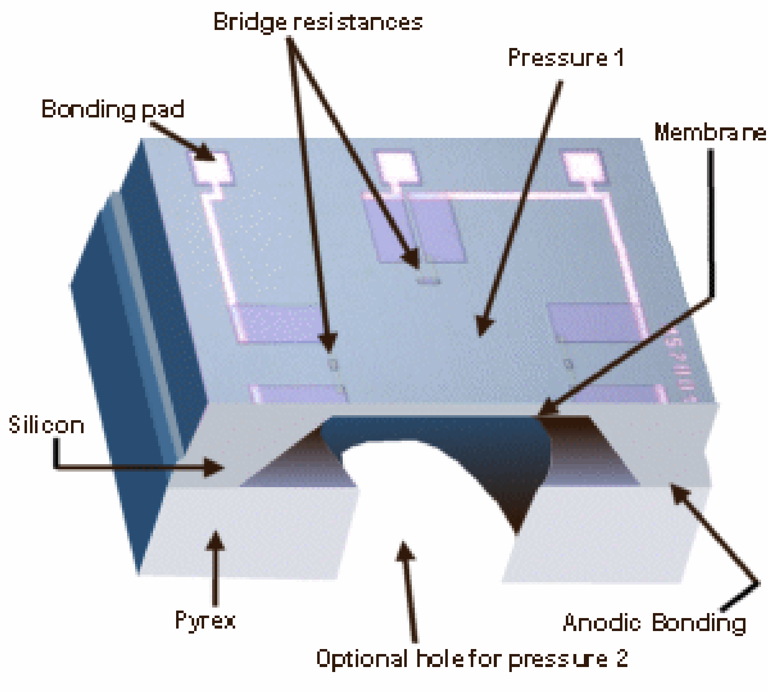
YOLE Développement

Altimeter/Barometer Module in CE

- **Piezoresistors by Ion Implantation**
- **Precise electrochemical etch stop (Critical Process Step for thin membrane)**
  - **Originally developed by B. Kloeck et al. @ IMT (Neuchatel)**

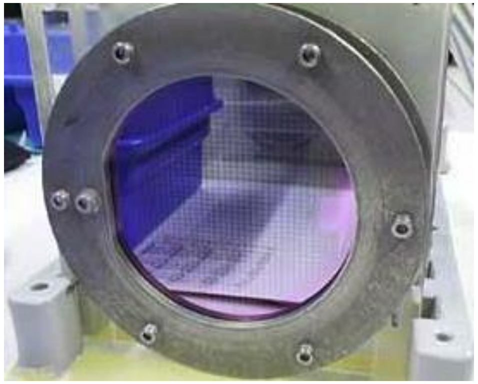
    B. Kloeck, S. D. Collins, N.F. de Rooij. R.L. Smith, "*Study of electrochemical etch-stop for high-precision thickness control of silicon membranes*", IEEE Transactions on Electron Devices, Vol. 36, April 1989, pp 663-669.
- **Anodic bonding of glass wafer**
- **Successful transfer to *Intersema Sensoric SA, CH (now TE Connectivity)***

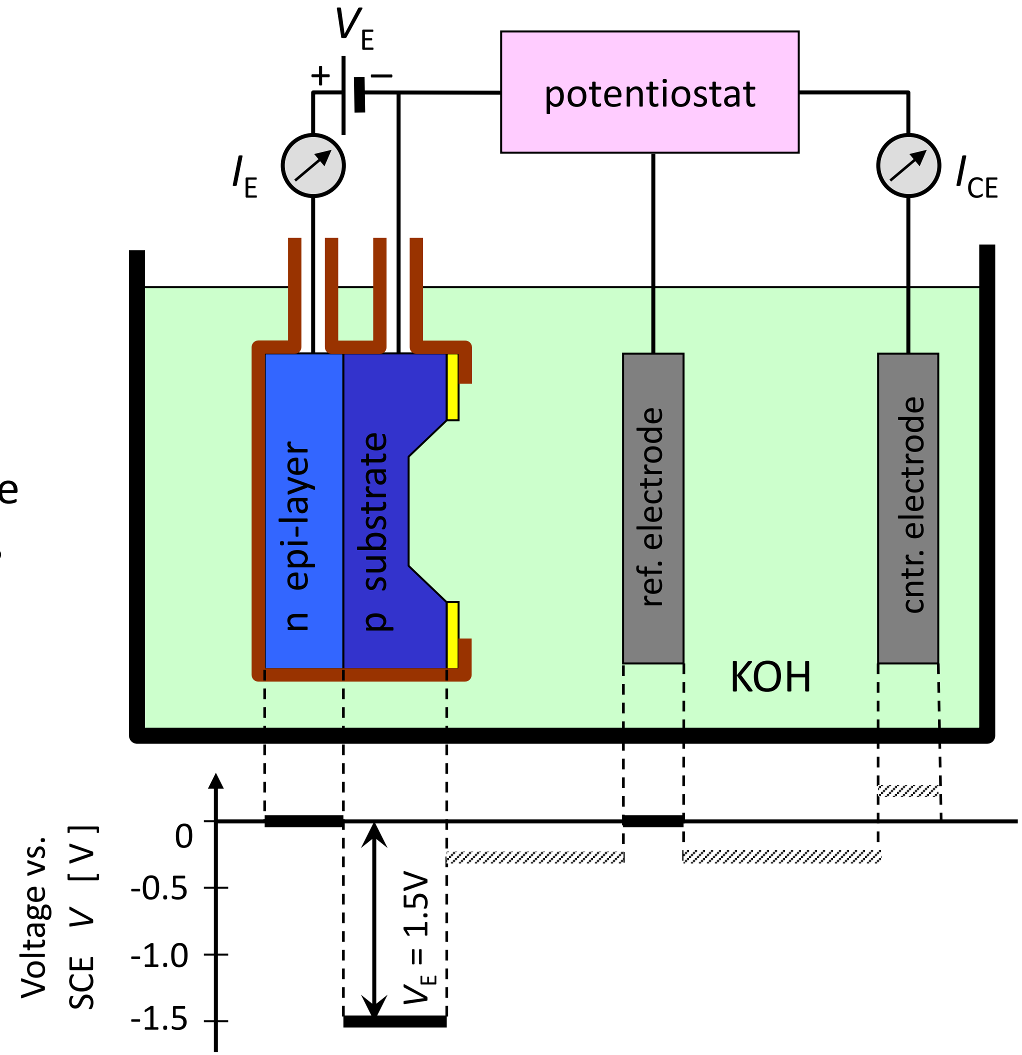
  (main supplier of watch market (barometric pressure/altimeter module)



Pressure Sensor: Membrane Etching

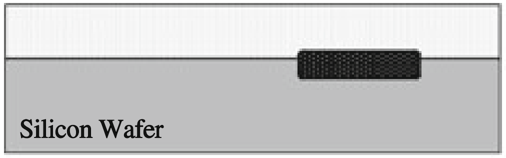
- Four-electrodes
- Electrochemical etch-stop
  n-doped silicon is not etched
- Voltage distribution w.r.t. SCE
  reference electrode
- n-p Diode prevents current flowing
  until p substrate is fully etched
- Current flow causes oxidation of the
  surface of n-epi layer preventing its
  etching by KOH





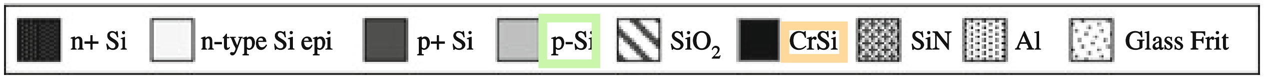
Pressure Sensor from Freescale

- Integrated bipolar transistors
  → Strong signal
- Strain sensor made of p-Silicon
- CrSi resistors for calibrating the sensor offset; fine tuned by laser trimming at end
- Electrochemical etching of cavity



(a) Starting wafer p-type silicon substrate, followed by n+ diffusion to create bipolar buried layer. Then a 15 micron thick layer of n-type silicon is deposited using epitaxy.

Warning: Wrong description on recorded lecture



Source: Reza Ghodssi, Pinyen Lin (Editors), "MEMS Materials and Processes Handbook", Springer, 2011, DOI 10.1007/978-0-387-47318-5,

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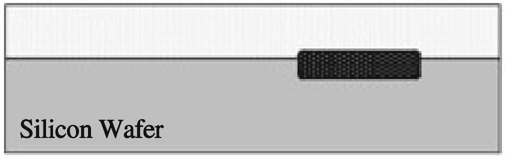
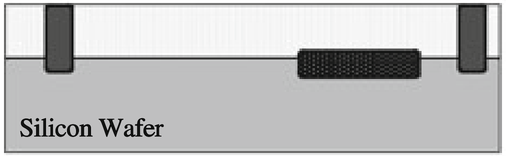
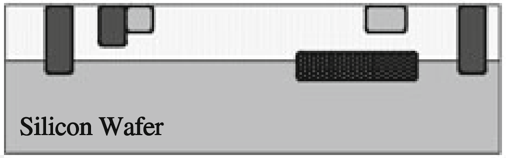


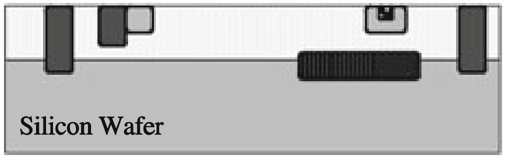
(a) Starting wafer p-type silicon substrate, followed by n+ diffusion to create bipolar buried layer. Then a 15 micron thick layer of n-type silicon is deposited using epitaxy.



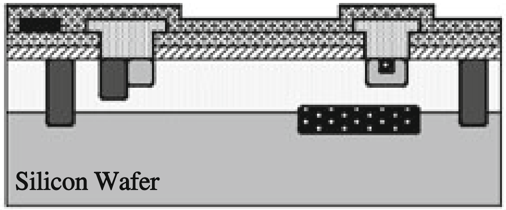
(b) Deep p+ diffusions are performed to form isolation for the bipolar transistors.



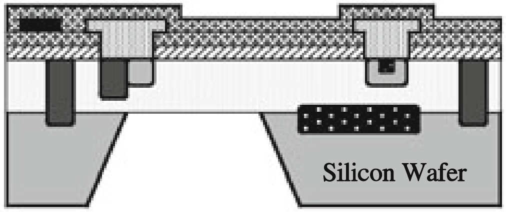
(c) A p+ diffusion is performed to form low-resistance connections and a p- diffusion is performed to make the piezoresistor element.



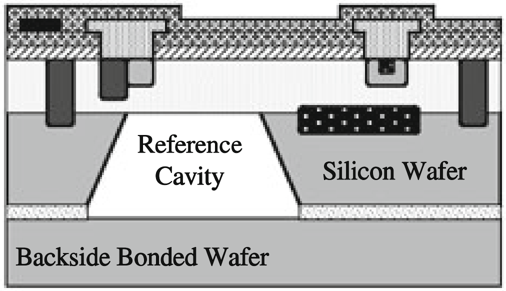
(d) A n+ diffusion is performed to form emitter for bipolar transistor formation.



(e) Chrome silicide resistors are formed that will be laser-trimmed o calibrate the pressure sensor after packaging. Then a 1.5 micron thick aluminum layer is deposited and patterned to electrically contact and connect the devices. A passivation layer of silicon nitride is then deposited using PECVD. The SiN is removed from the bond pads.



(f) A backside wet anisotropic etch is performed using an electrochemical etch stop created by biasing the epi layer.



(g) Optional: a wafer is bonded to the backside using glass frit to create a sealed reference cavity for absolute pressure sensor.

▦ n+ Si ☐ n-type Si epi ■ p+ Si ▒ p-Si ▧ SiO$_2$ ■ CrSi ▩ SiN ▥ Al ░ Glass Frit

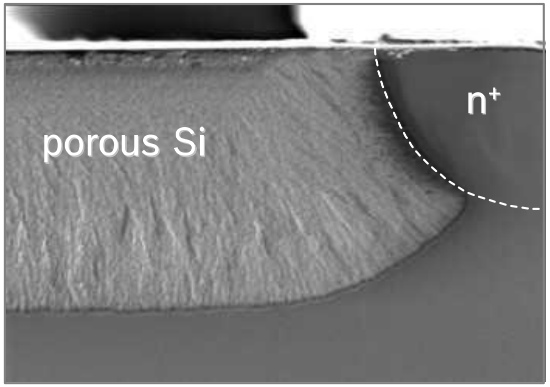
Source: Reza Ghodssi, Pinyen Lin (Editors), "MEMS Materials and Processes Handbook", Springer, 2011, DOI 10.1007/978-0-387-47318-5,

Pressure Sensor from Bosch with APSM Technology

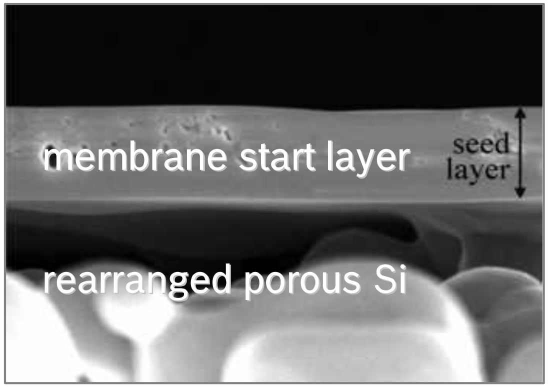
➔ APSM technology (Advanced porous silicon membrane)

- anodic etching generates porous silicon
- porous silicon transforms into a vacuum cavity by sintering
- monocrystalline membrane is grown with epitaxy
- process is fully CMOS compatible

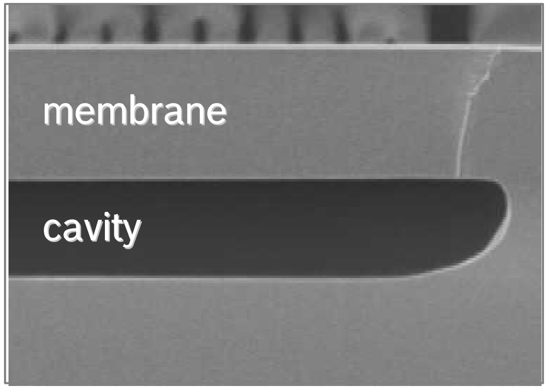
after anodization



after prebake



after epitaxy



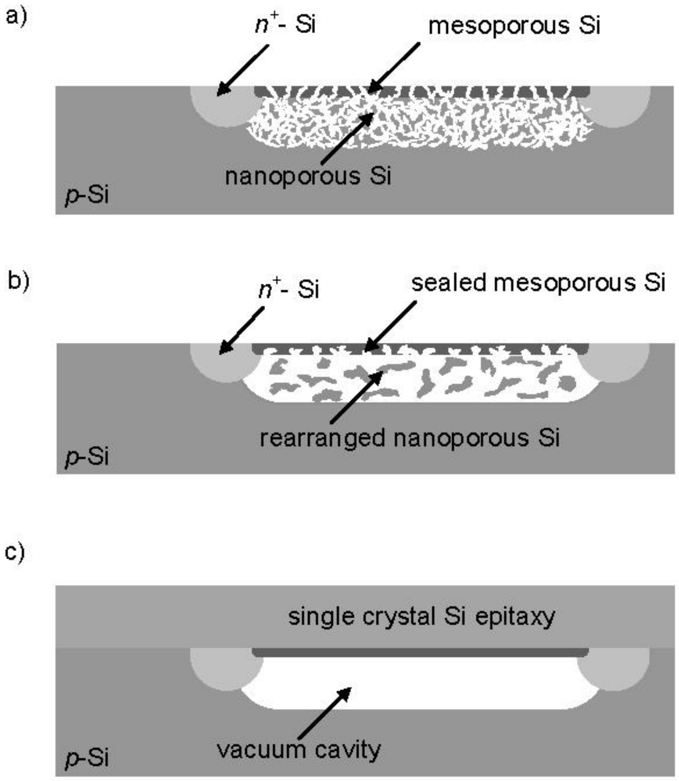
Automotive Electronics

BOSCH

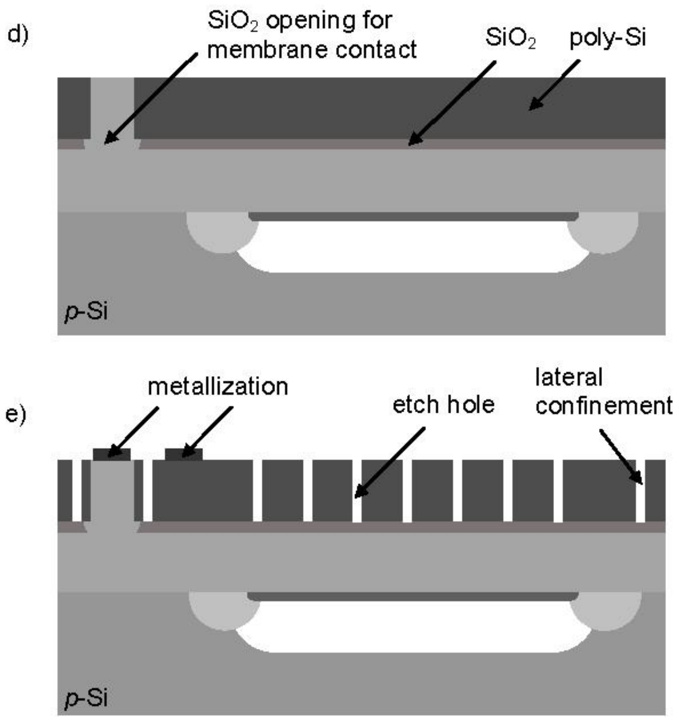
Detailed description: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1215299

Pressure Sensor from Bosch with APSM Technology

- **Integrated cavity formation**
- **APSM: Advanced Porous Silicon Membrane**

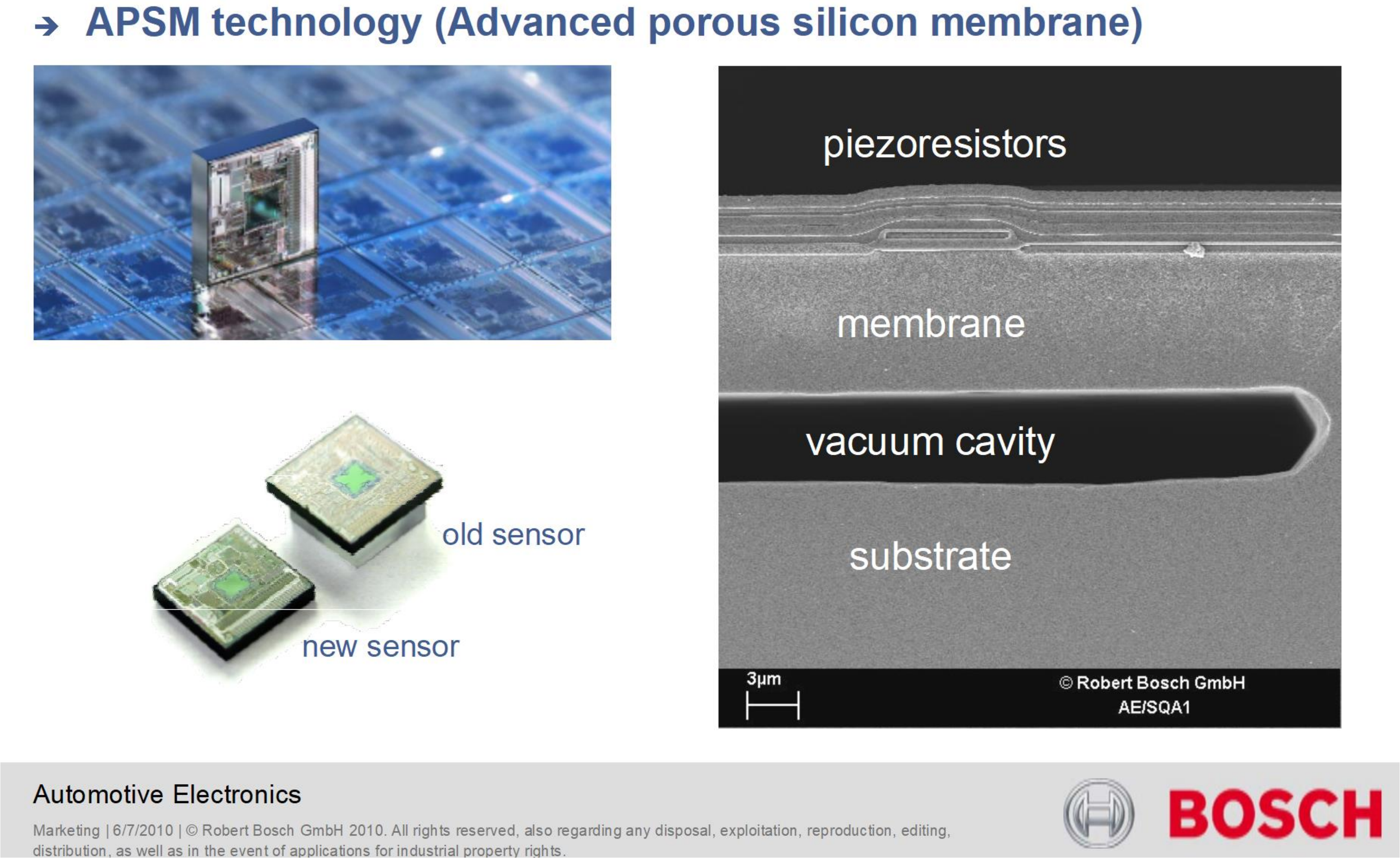


Capacitive sensor schematic



Source: Knese et al. IEEE MEMS Conference 2009; DOI: 10.1109/MEMSYS.2009.4805478
Detailed description: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1215299

Pressure Sensor from Bosch with APSM Technology



→ **APSM technology (Advanced porous silicon membrane)**

Automotive Electronics

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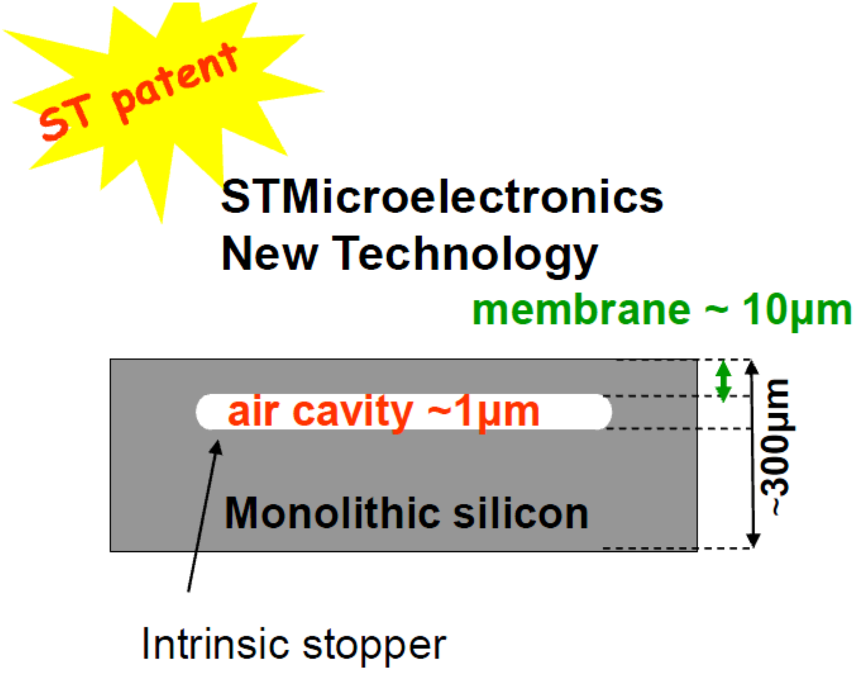
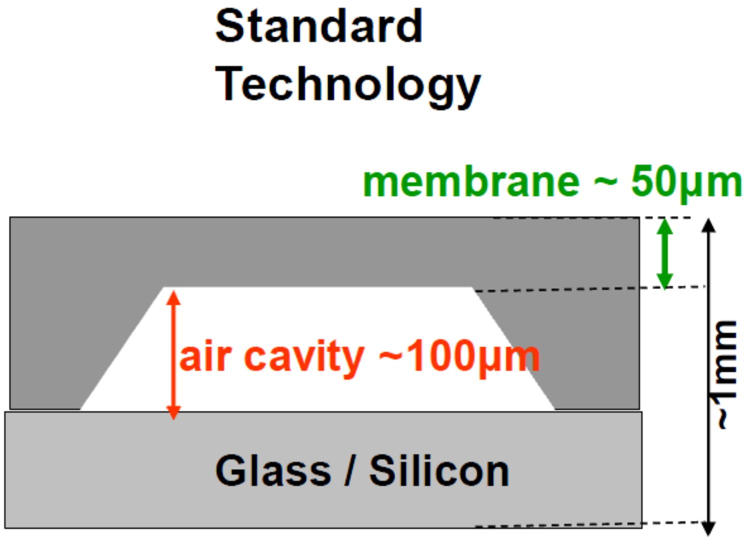
Detailed description: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1215299

Pressure Sensor from ST with VENSENS Technology

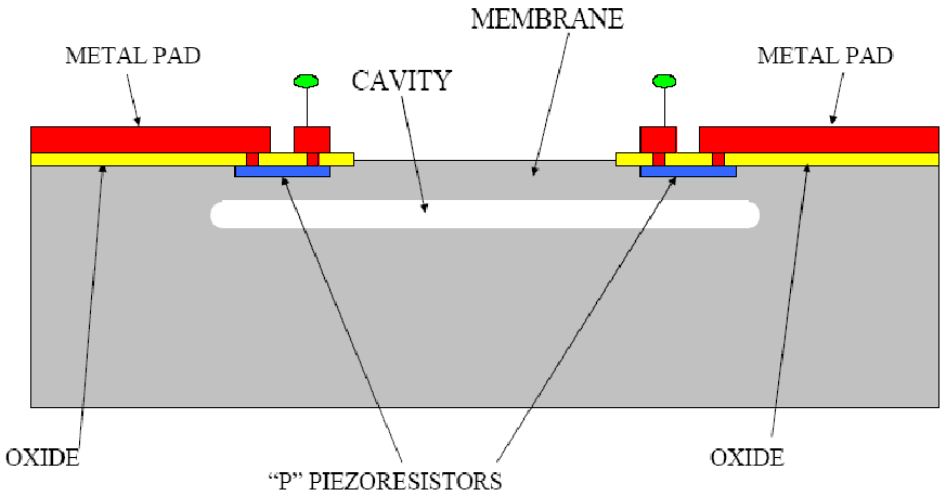




Monolithic monosilicon sensor with hermetic cavity

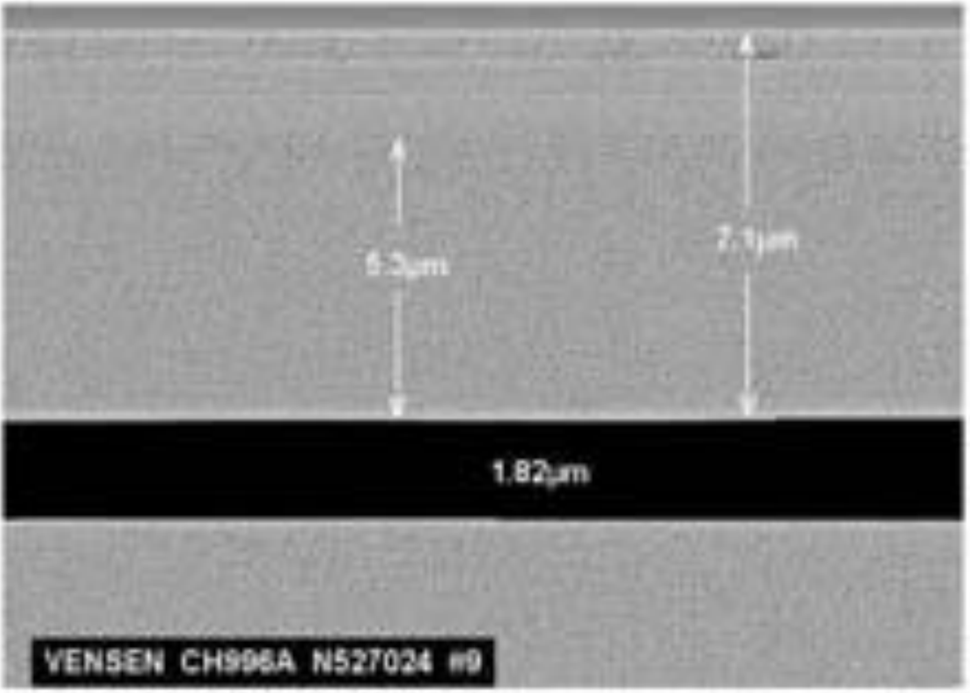
Silicon membrane bonding with glass/silicon wafer to create the cavity

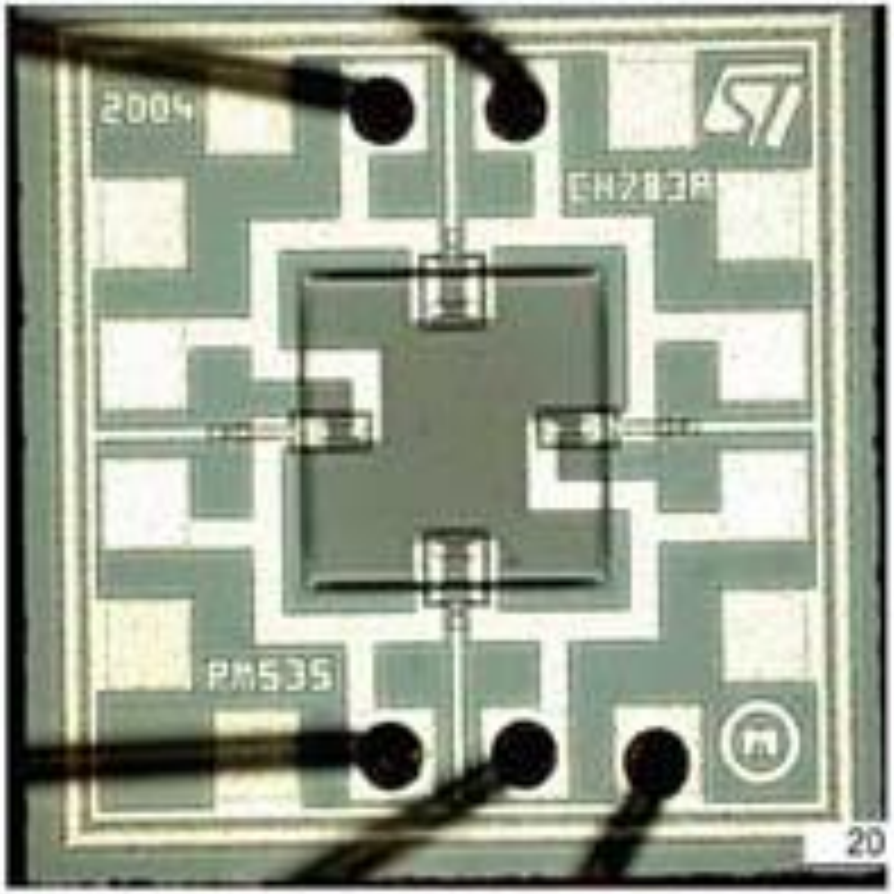
Pressure Sensor from ST with VENSENS Technology



- No wafer to wafer bonding for cavity creation
- Thinner and smaller chip
- Intrinsic stoppers
- High Shock Survivability
- Stable and Reliable

Pressure Sensor from ST with VENSENS Technology

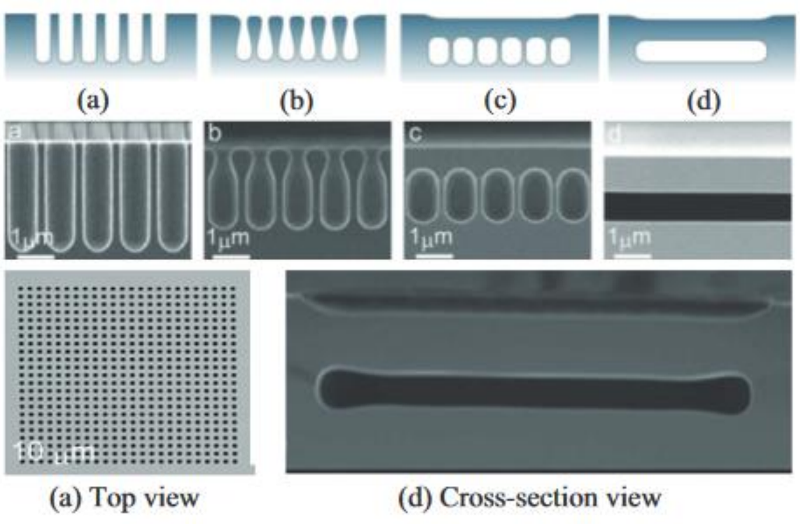




Pressure Sensor from ST with “VENSENS” Technology

Based on silicon migration process

- DRIE of trenches
- Annealing at < 1000° C in H_2
- Heat-treatment induces the surface migration of silicon to minimize the surface energy, leading to widening of the void at the base and shrinking of the opening at the top, reaching coalescence of the voids at the bases of adjacent trenches and closing of the space at the top

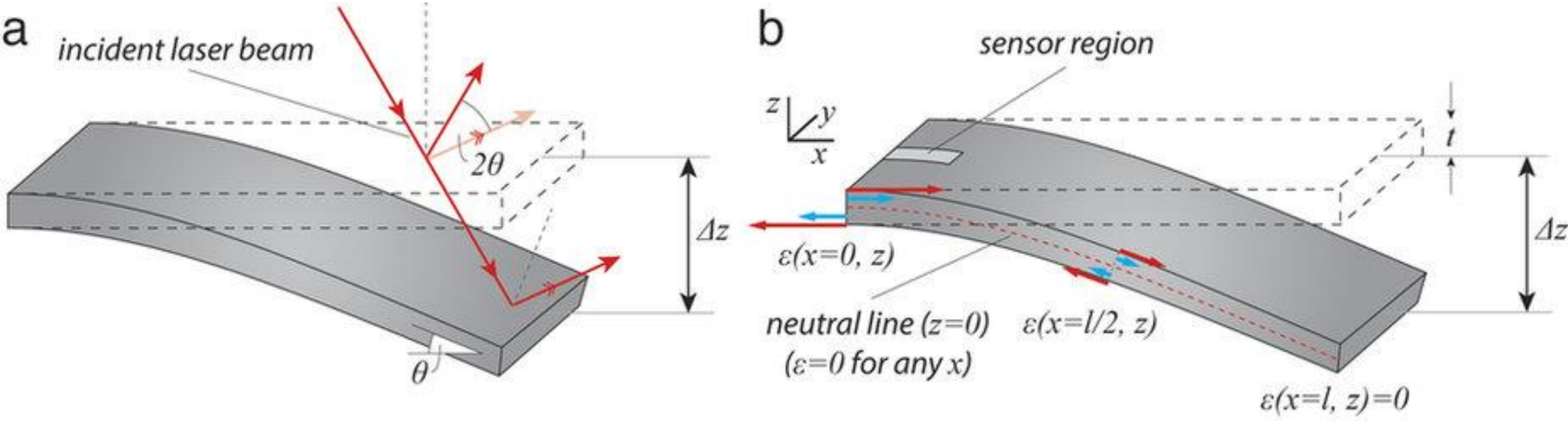


Jiale Su et al., J. Semicond. (2018) 39 071005

Case Study

MEMS AFM CANTILEVER

Piezoresistive AFM Cantilever



- **Optical Beam Deflection (OBD)**
- **Deflection**

$$\theta = \frac{3}{2l}\left(1 - \left(\frac{l_b}{2l}\right)^2\right) \cdot \Delta z \qquad (1)$$

- **Piezoresistive Readout**
- **Strain**
- **Maximum at top/bottom**

$$\varepsilon = \frac{3}{2} \cdot \frac{(t - t_s)(1 - l_s/2l)}{l^2} \cdot \Delta z \qquad (2)$$

- **Length: decrease will increase the measured signal for a given displacement in both readouts**
- **Thickness: increases stress readout.**

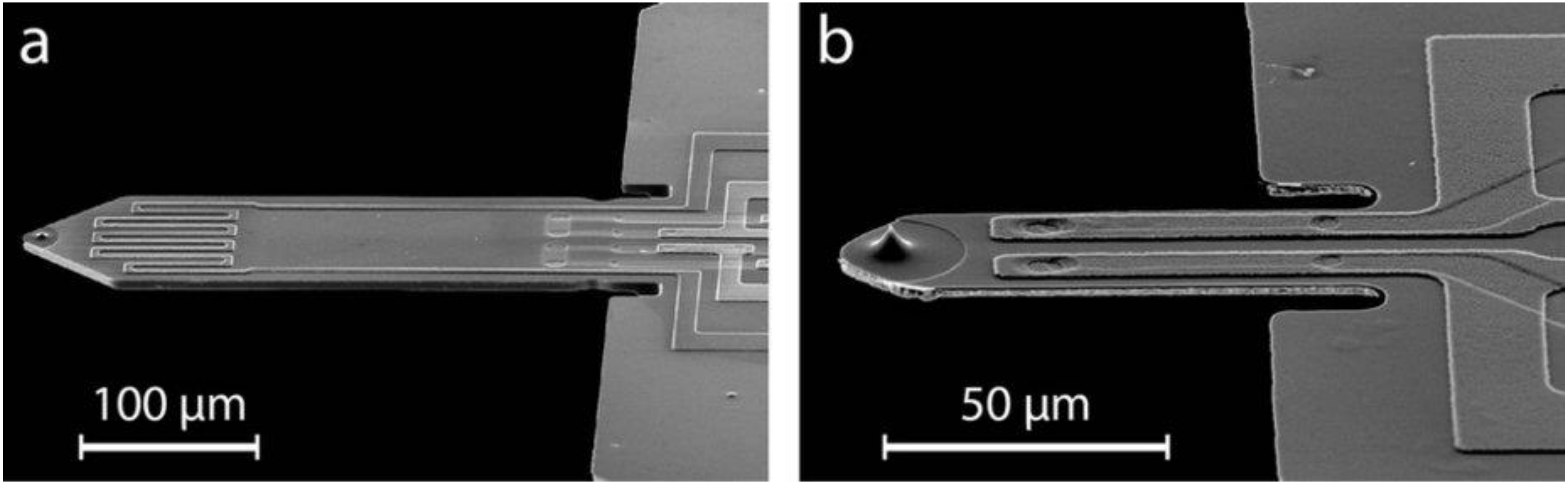
Dukic, Adams & Fantner, http://www.nature.com/articles/srep16393

Piezoresistive AFM Cantilever

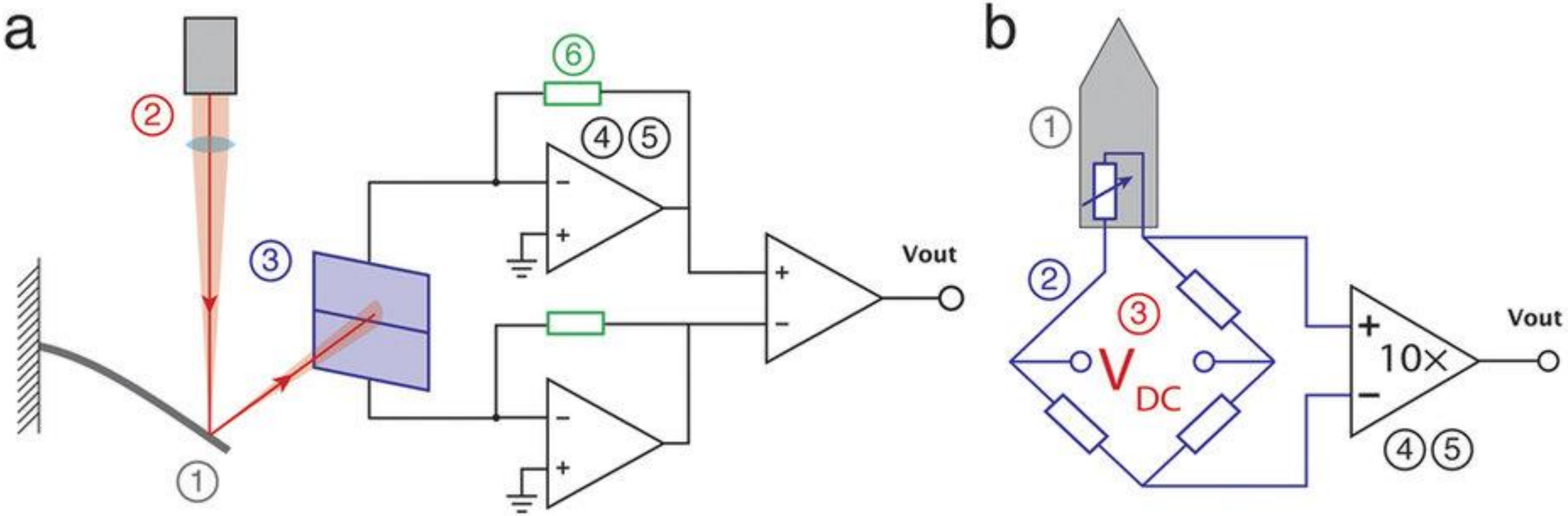
- PRSA and PRS probes, SCL-Sensor. Tech. Fabrication GmbH, Austria
- thickness from 4–6 µm
- resonance frequency
    - 80 kHz (300 × 100 µm)
    - 850 kHz (70 × 30 µm)
- mechanical bandwidth
    - 0.8 kHz (300 × 100 µm)
    - 3 kHz (70 × 30 µm).

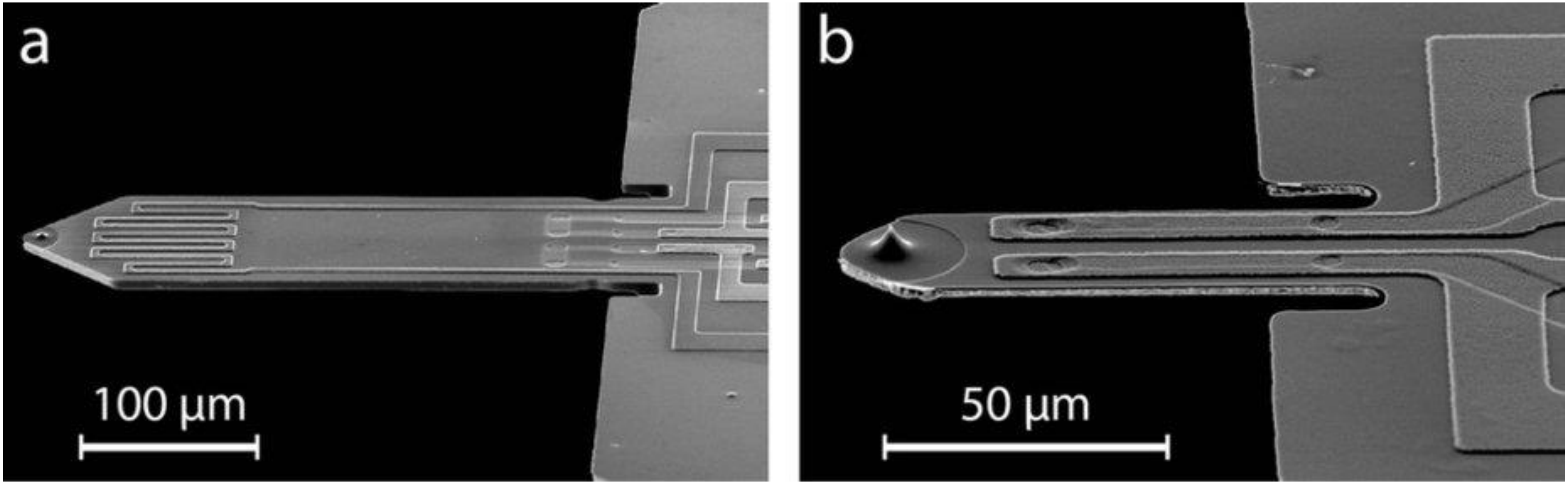
http://www.sclsensortech.com/

Dukic, Adams & Fantner, http://www.nature.com/articles/srep16393

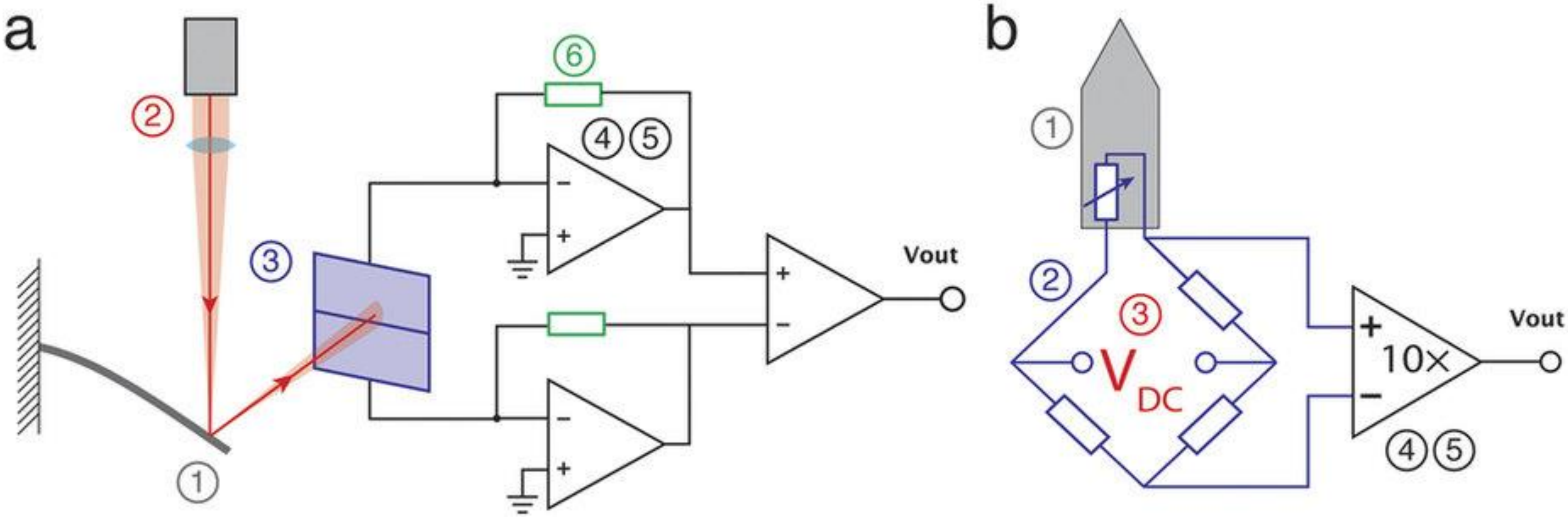


Piezoresistive AFM Cantilever





Piezoresistive AFM Cantilever



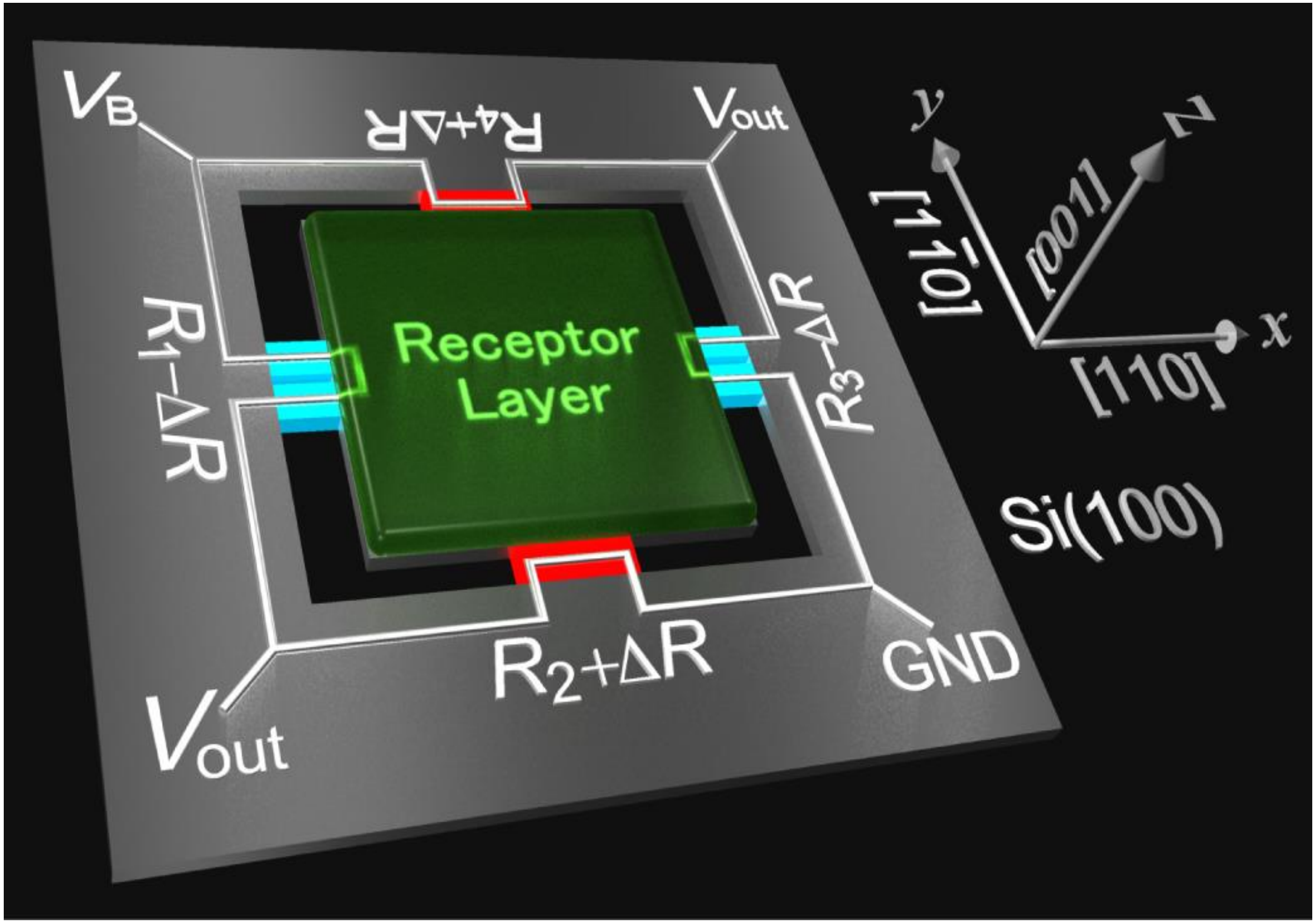
- **piezoresistive sensors measure strain in cantilever**
- **best suited for cantilevers with larger thickness and higher spring constants**
- **small-sized cantilevers can have equal or better AFM imaging noise performance using piezoresistive readout than using optical beam deflection OBD readout**
- **-> no optical readout required! in-situ measurement.**

Dukic, Adams & Fantner, http://www.nature.com/articles/srep16393

Case Study

SURFACE STRESS SENSOR

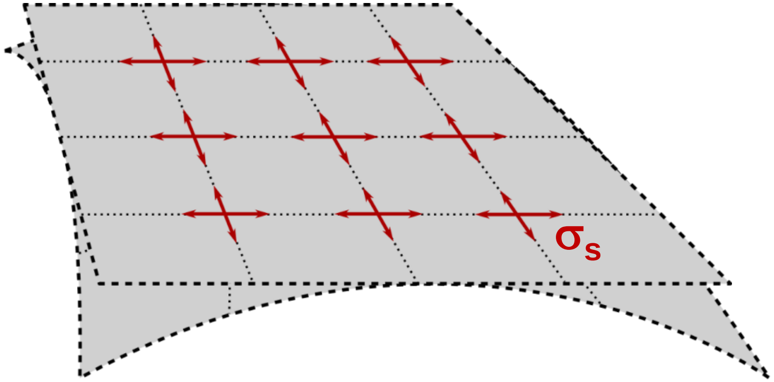
Membrane-type Surface Stress Sensor (MSS)



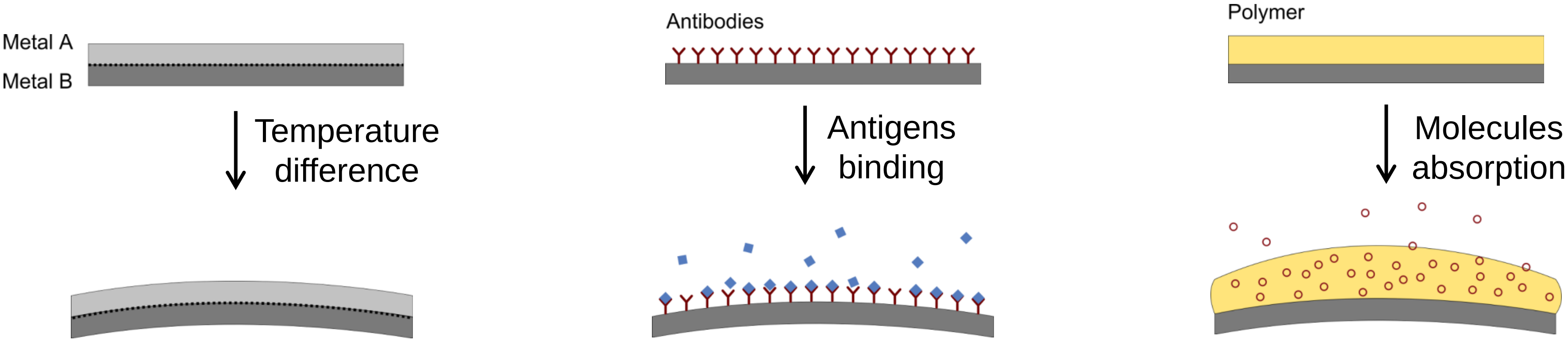
G. Yoshikawa, T. Akiyama, S. Gautsch, P. Vettiger, H. Rohrer, Nano Letters 11, 1044 (2011)

What causes Surface Stress ?

- **Physical effect of surface stress**

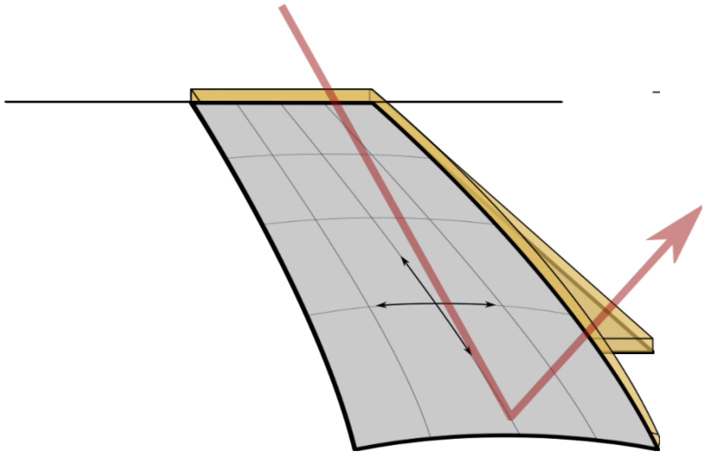


- Sources of surface stress

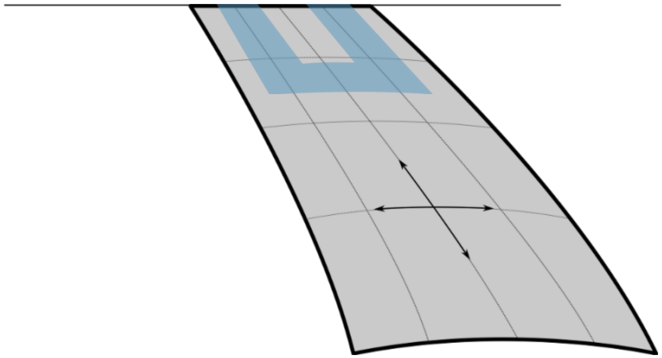


Cantilever-Based Sensors for Surface Stress Sensing

- **Optical or integrated detection mode**



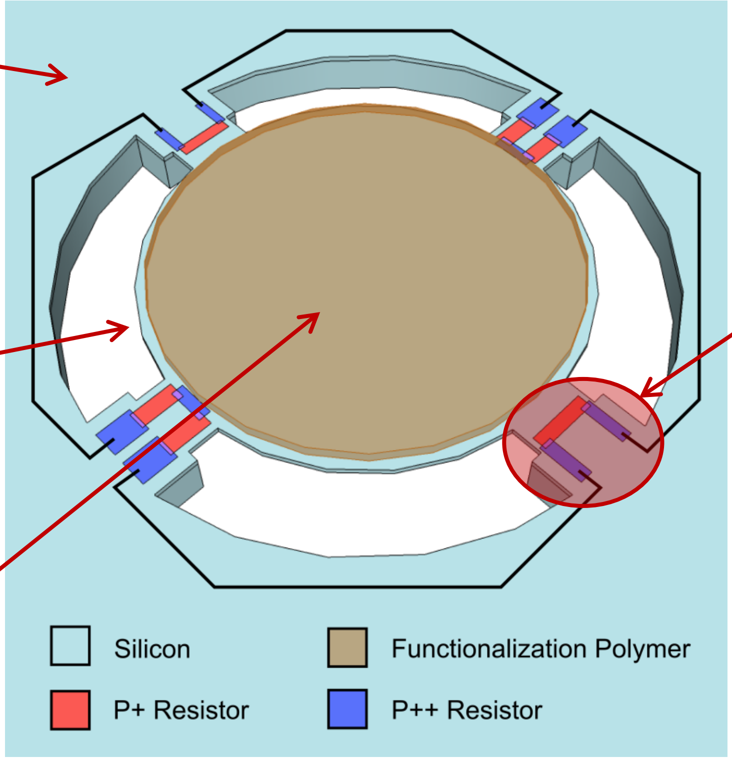
+ Very sensitive
- Bulky
- Does not work in opaque liquid



+ Portable system
- Less sensitive

- Surface Stress is not equal to mass sensing (no frequency shift) !
- The sensitivity does not scale with the active area of the cantilever

Main Characteristics of a Membrane-Type Sensor



SOI wafer
released by DRIE

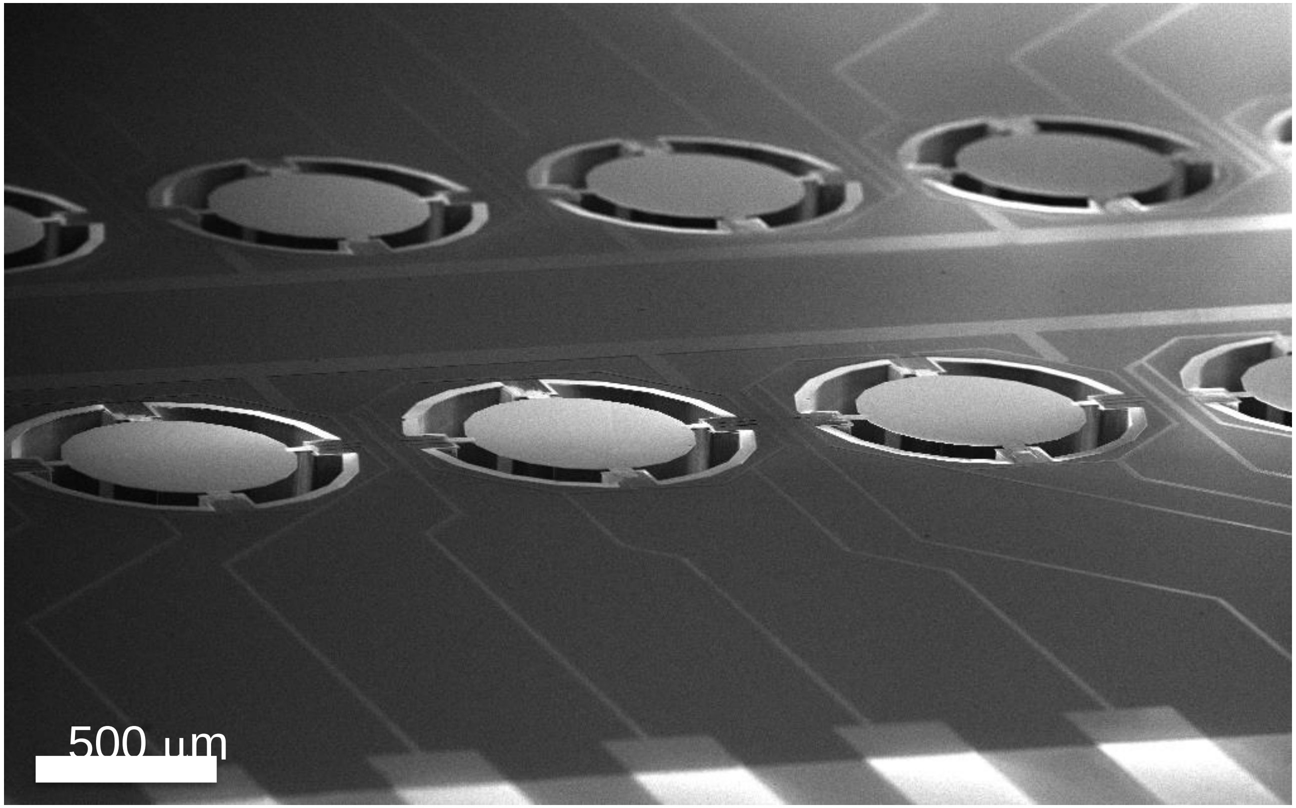
Diameter: 500 μm
Thickness: 2.5 μm

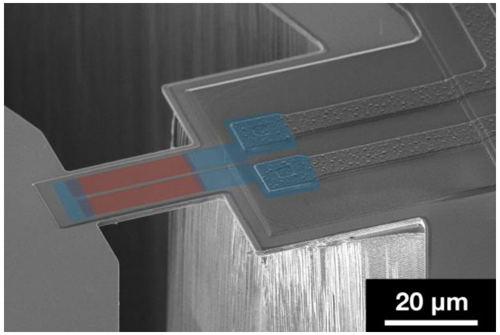
Polymer deposited
by inkjet printing

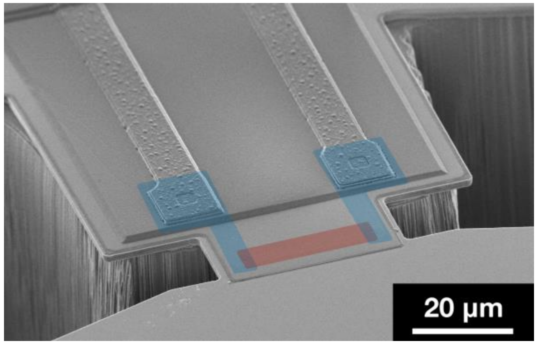
- Shallow piezoresistors created by ions implantation (p+)
- Deep contacts created by ions diffusion (p++)

- Low voltage (1-2 V)
- Full Wheatstone Bridge
- DC operation

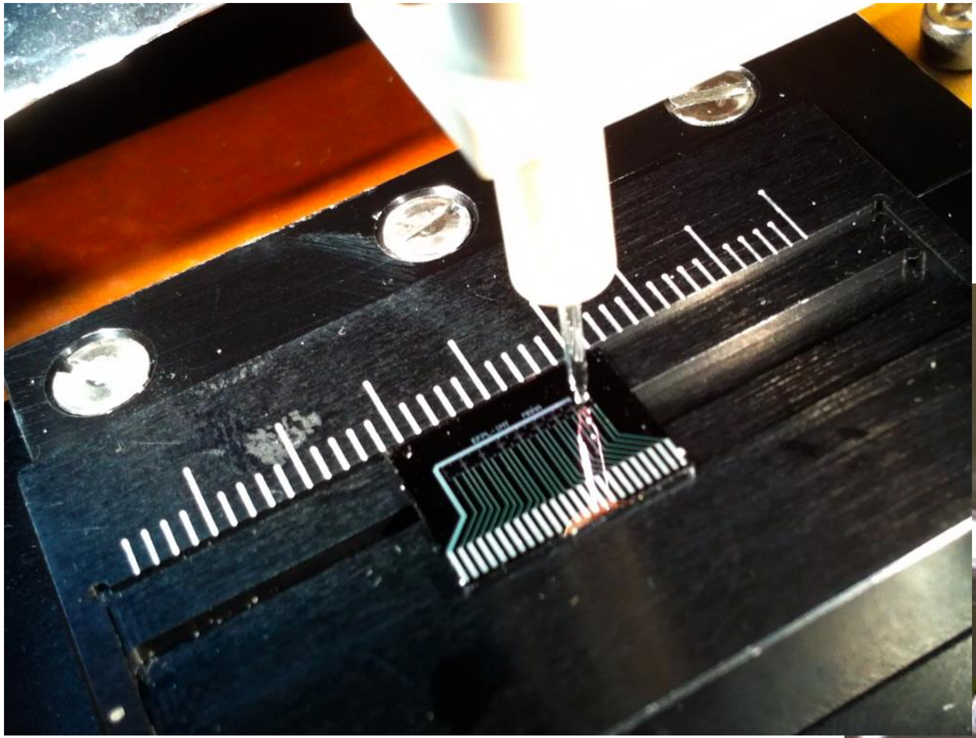
MSS SEM characterization

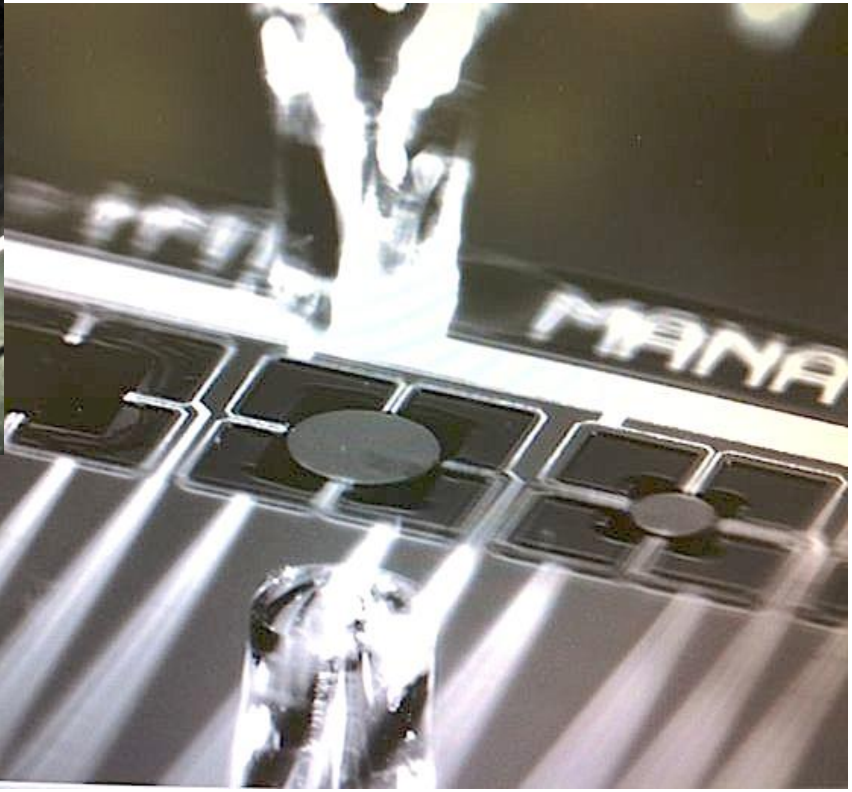






Functionalization of MSS by inkjet spotting

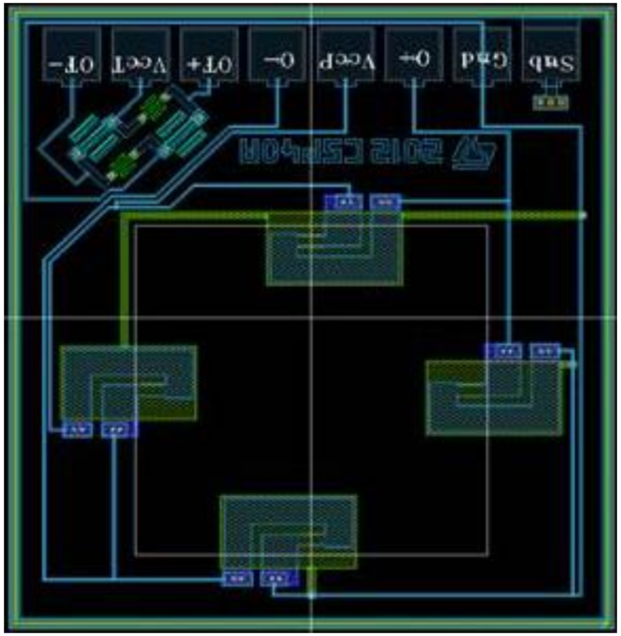


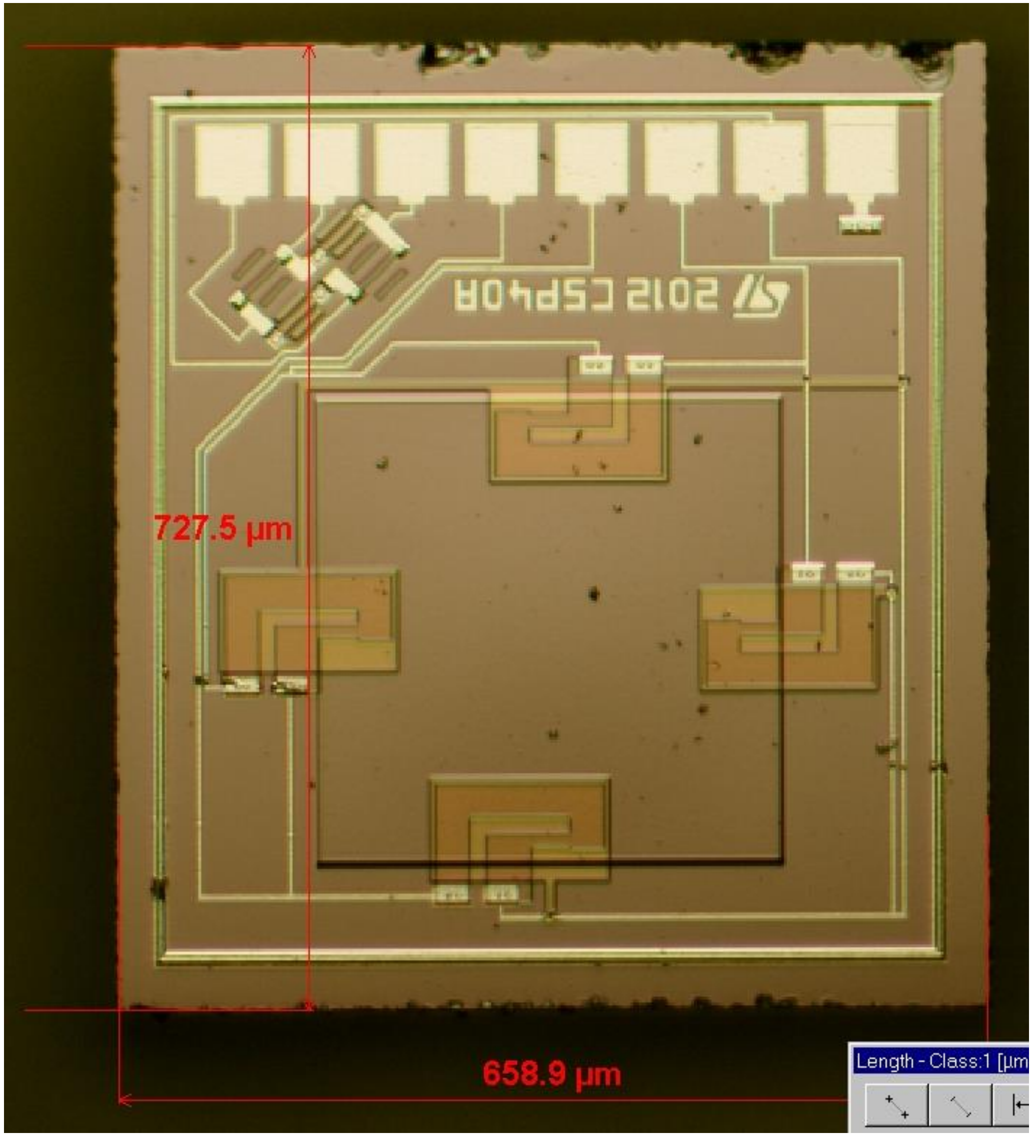


Courtesy of
Hans-Peter Lang
(Physics, UNIBAS)

G. Yoshikawa, T. Akiyama, S. Gautsch, P. Vettiger, H. Rohrer, Nano Letters 11, 1044 (2011)

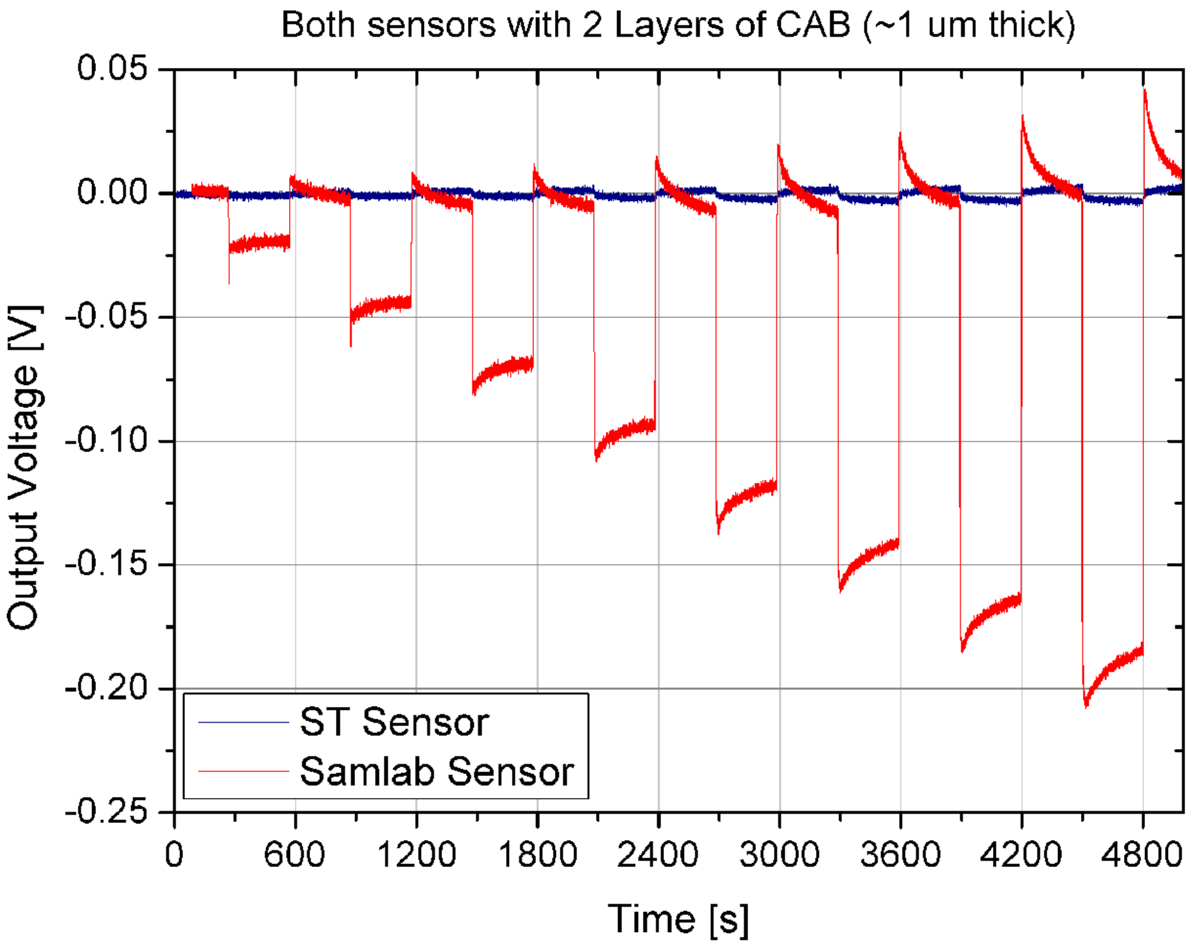
Comparison MSS H$_2$0 sensor with ST pressure sensor





Coated with CAB layer

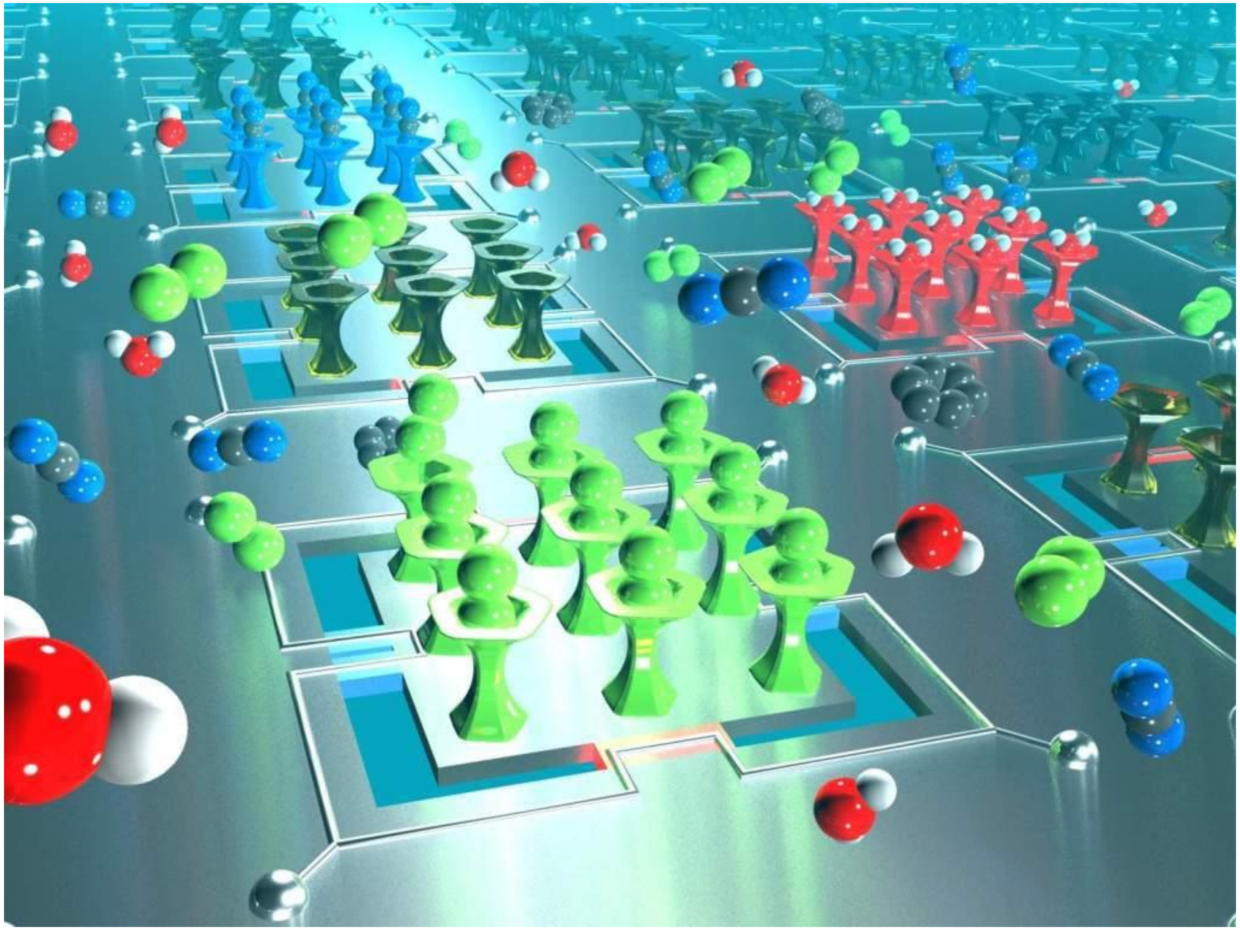
Comparison MMS H_20 sensor with ST pressure sensor



Samlab sensor with MSS design

Membrane-type Surface Stress Sensor (MSS)

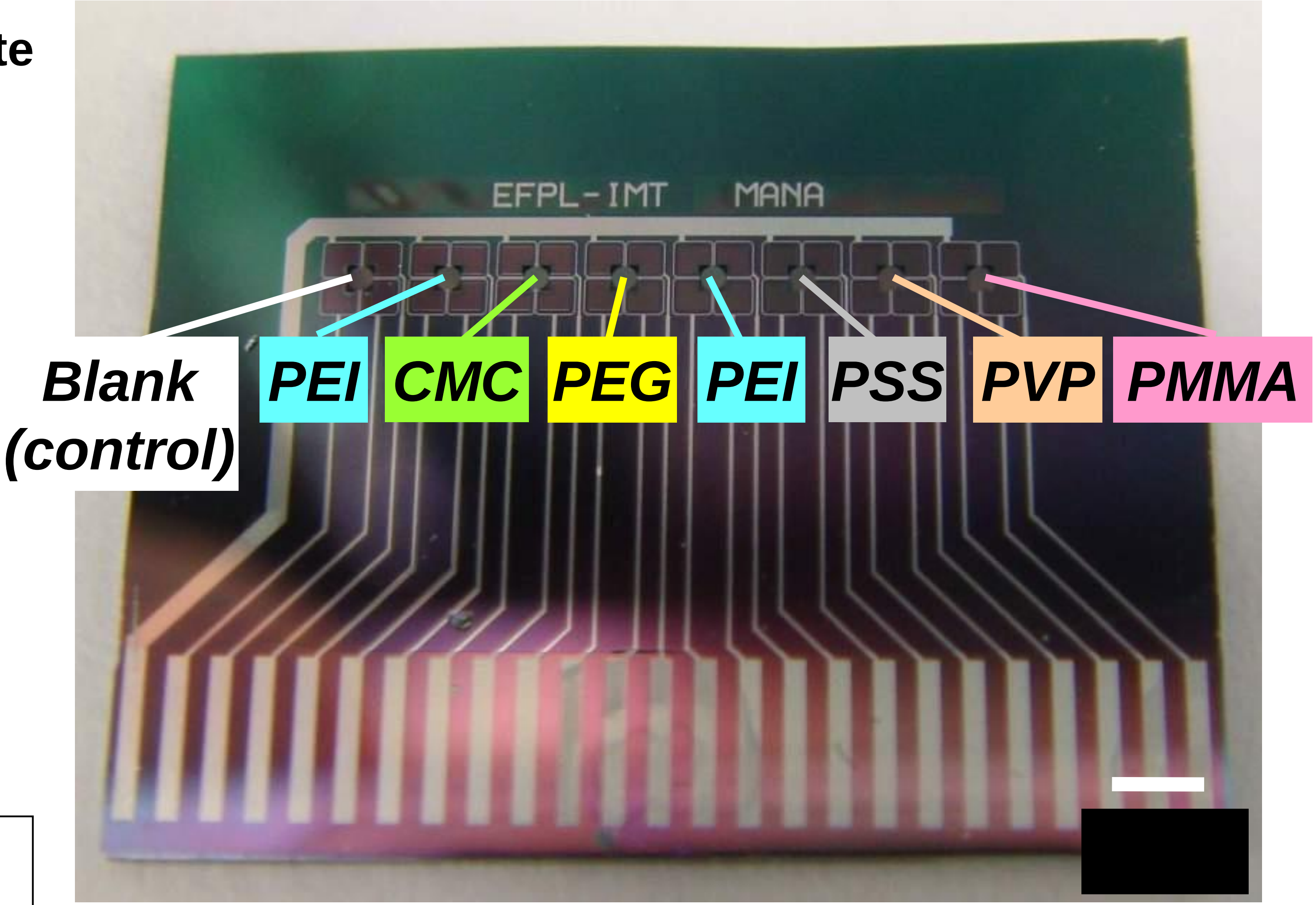
For multi-analyte detection



G. Yoshikawa, T. Akiyama, S. Gautsch, P. Vettiger, H. Rohrer, Nano Letters 11, 1044 (2011)

MSS Functionalization with polymers by inkjet spotting

For multi-analyte detection



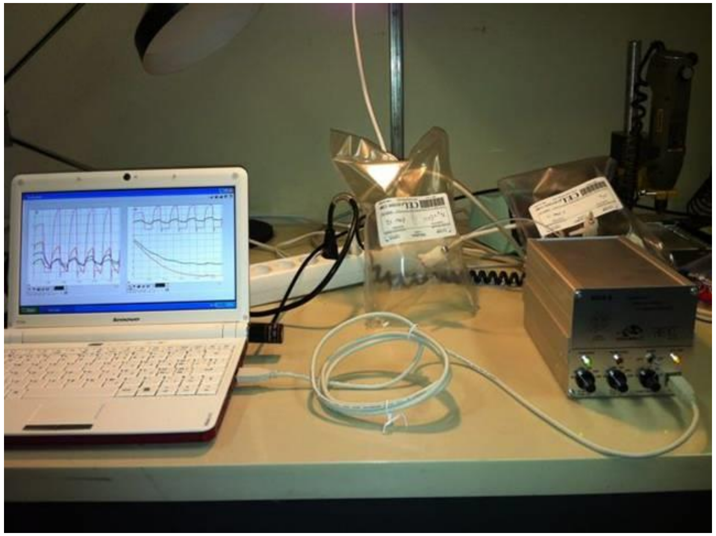
[redacted]

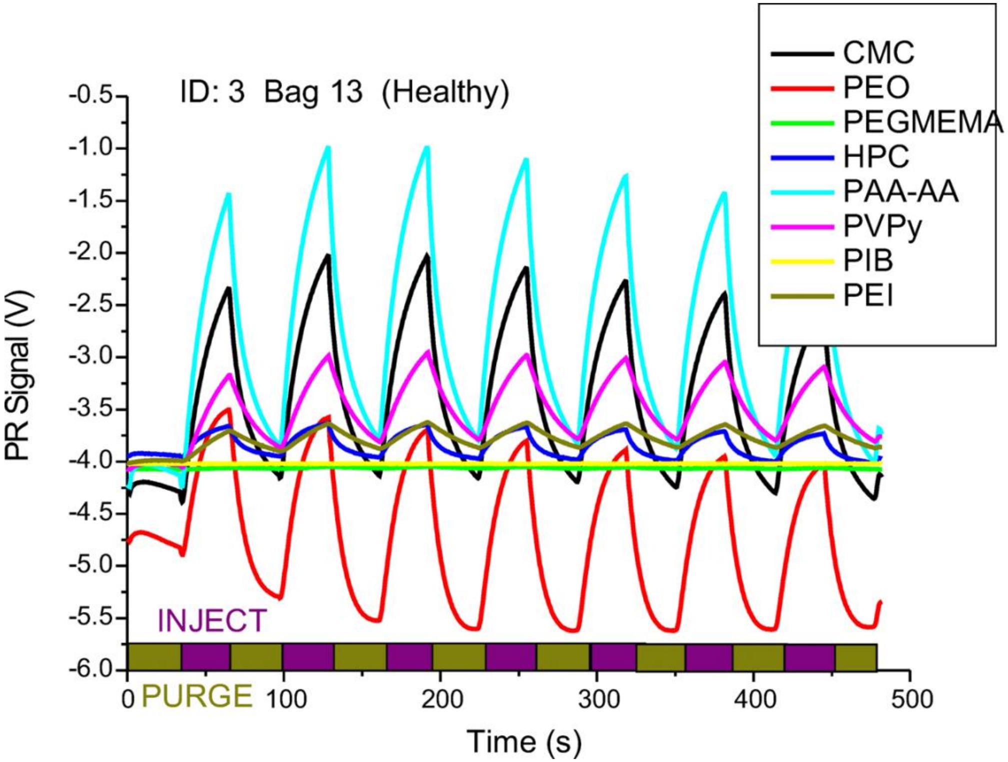
Courtesy of Genky Yoshikawa (MANA, NIMS)

G. Yoshikawa, T. Akiyama, S. Gautsch, P. Vettiger, H. Rohrer, Nano Letters 11, 1044 (2011)

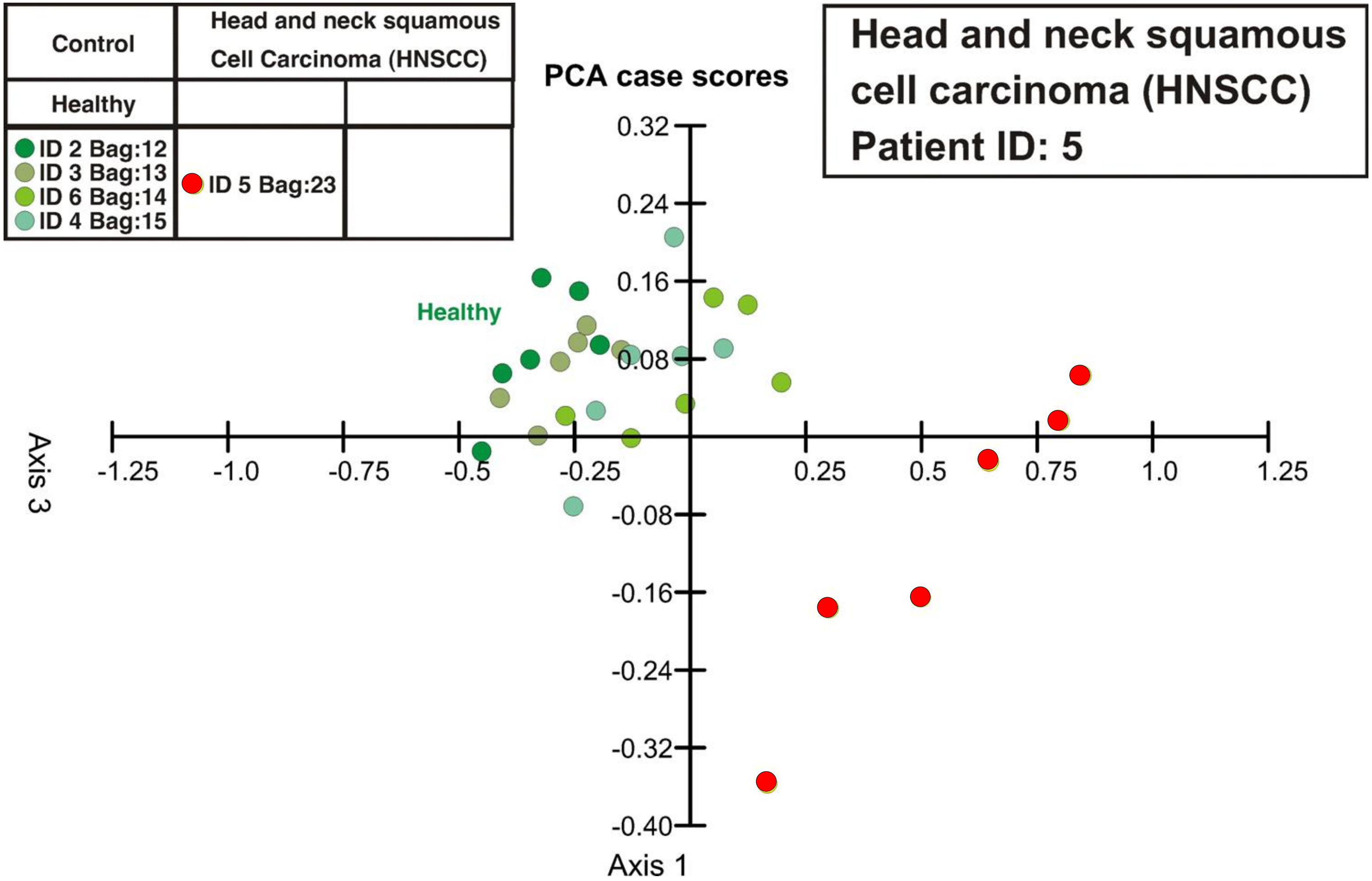
MSS sensors: Cancer diagnosis via human breath analysis

- **Objectives**
  - **Cancer diagnosis with a portable and non-invasive tool**
  - **Exhaled breath analysis**
  - **Volatile Organic Compounds (VOCs) detection**

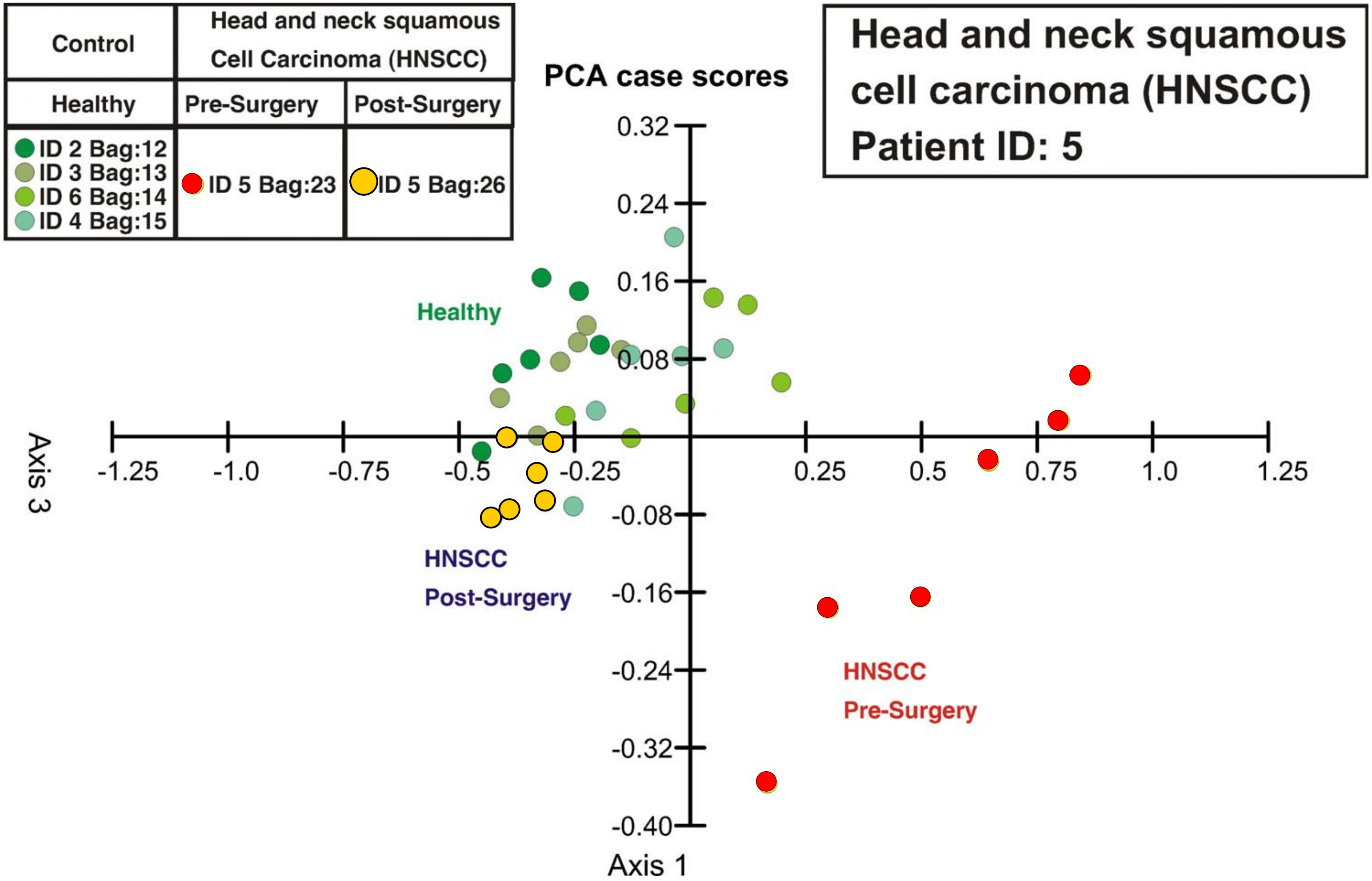




MSS sensor: PCA of human Breath samples



MSS Sensor: Breath Pre- and Post-Surgery



Summary Questions

- What can be measured with MEMS Sensors? How?
- Why (How) would an Engineer choose a MEMS sensor for an application?
- How does piezoresistive sensing work? Why MEMS?
- What is the Gauge factor, and what are its 2 contributions?
- Would you choose single crystalline or polycrystalline silicon for a piezoresistive pressure sensor? Why?
- Would you prefer p-type or n-type silicon for the piezoresistor material?
- Draw the orientation of a p-type piezoresistor to obtain maximum responsivity on a 100-wafer with a flat parallel to a <100>-direction.
- Draw a simple process flow for a piezoresistive pressure sensor.
- Describe different implementations of piezoresistive read-out in MEMS