Microsensors –

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sensonor

Outline

1. Classification of Sensors
2. Applications
3. MEMS Technologies
4. Pressure Sensors
5. Accelerometers
6. Gyroscopes

Based on:

Adriana Lapadatu, **"Microsensors"**,

1st e-CUBES Summer School, Uppsala Univ., 3-5 Sep. 2007,

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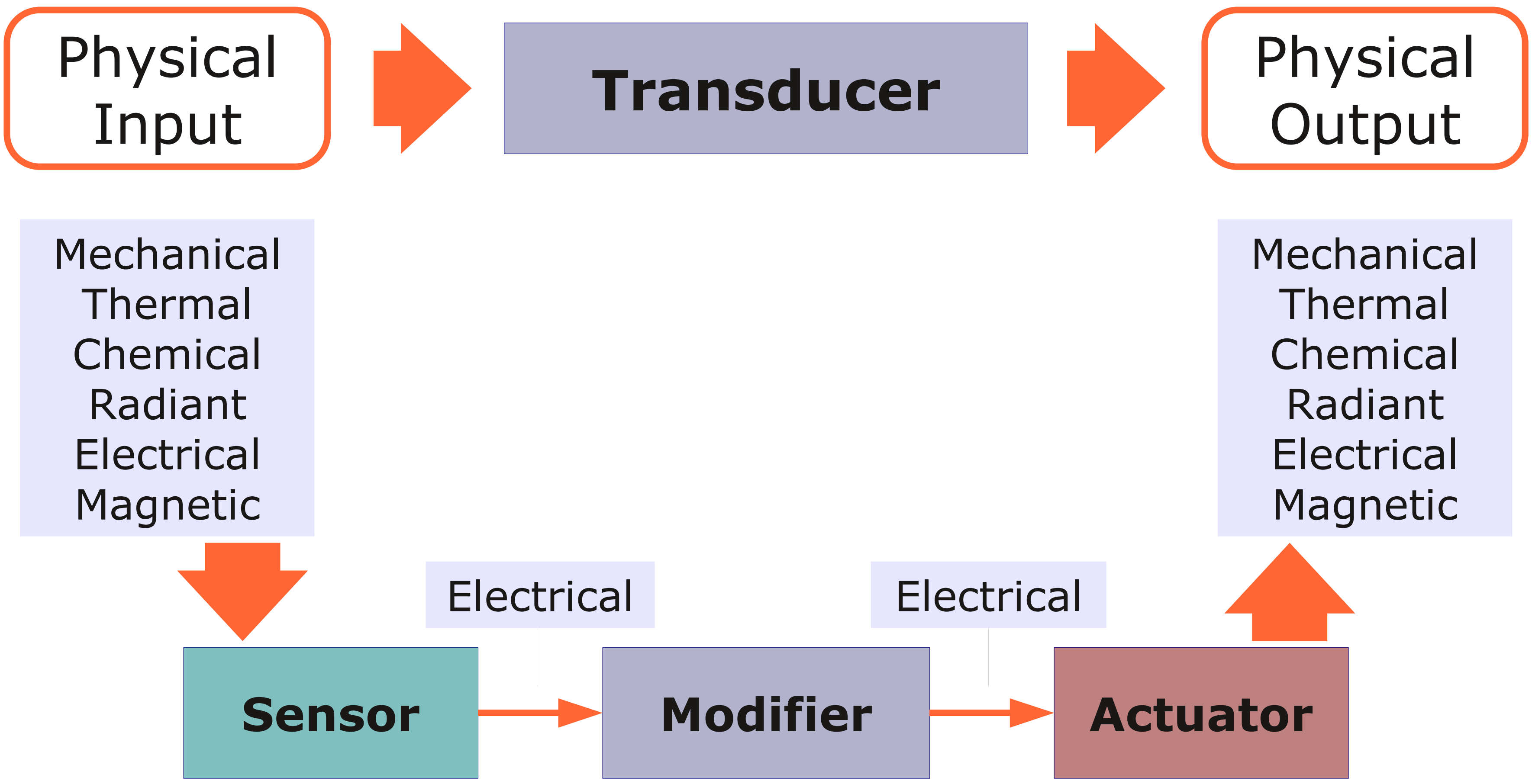
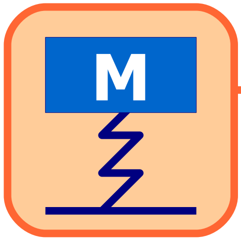
Transducers

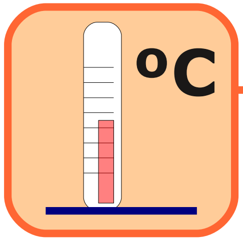


Classification of Sensors



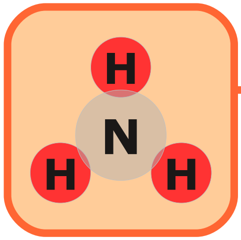
Mechanical

Force, acceleration, pressure, torque, flow, displacement, velocity, level, position, tilt...



Thermal

Temperature, heat, specific heat, entropy, heat flow...



Chemical

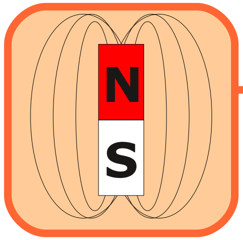
Composition, concentration, reaction rate...

Biosensors

Cells, sugars, proteins, hormones, antigens...

Radiation

Gamma rays, X-rays, ultra-violet, visible light, infrared, microwaves, radio waves...



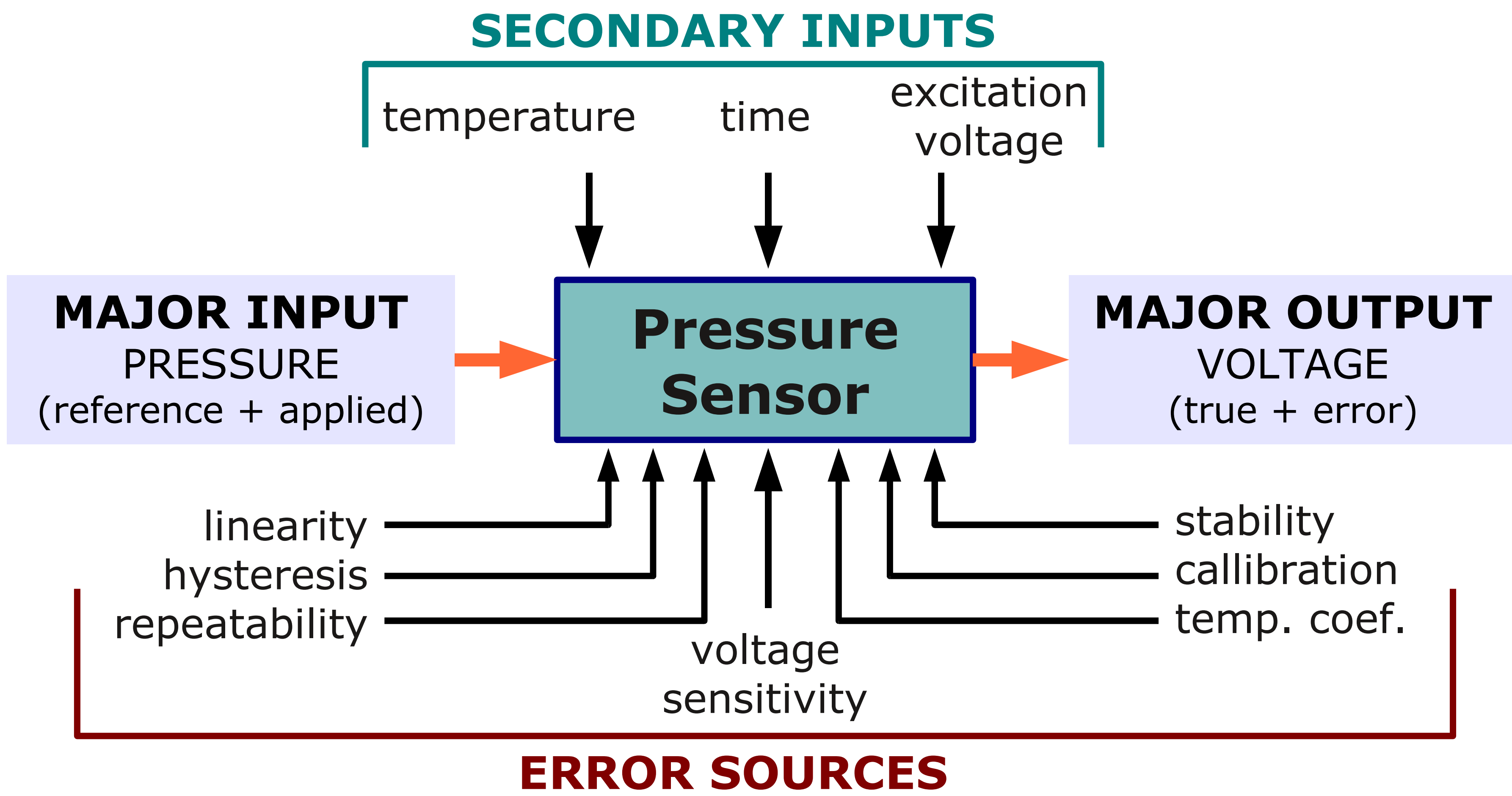
Magnetic

Field intensity, flux density, moment, magnetization, permeability...

MultiMEMS

Inputs and Outputs of Sensors

- Sensors transform a *physical* input into an *electrical* output.



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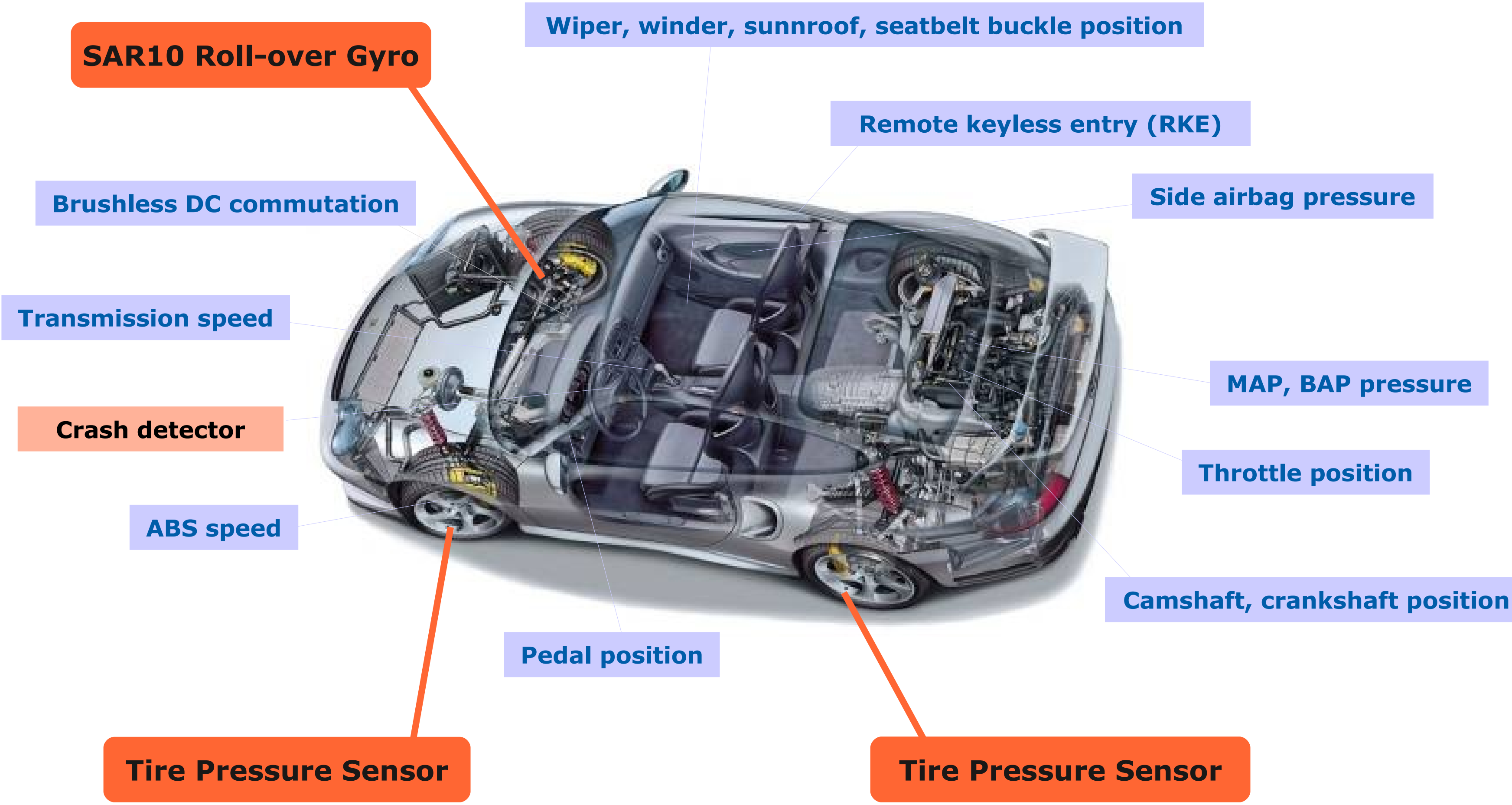
Automotive Applications



MultiMEMS

Examples of Automotive Applications

- Safety devices:
  - Airbag deployment,
  - Antilock braking systems (position sensors),
  - Suspension systems (displacement, position and pressure sensors),
  - Object avoidance (pressure and displacement sensors),
  - Navigation (gyroscope).
- Engine and power train:
  - Manifold control with pressure sensors,
  - Airflow control,
  - Exhaust gas analysis and control,
  - Fuel pump pressure and fuel injection control,
  - Transmission force and pressure control.
- Vehicle diagnostics and health monitoring:
  - Engine oil pressure,
  - Tire pressure,
  - Brake oil pressure,
  - Transmission fluid,
  - Fuel pressure.
- Comfort:
  - Seat control,
  - Air quality and flow,
  - Air temperature and humidity,
  - Satellite navigation.

Medical Applications

- Disposable blood pressure sensors (17 millions units per year);
- Intrauterine pressure sensor (1 millions units per year);
- Infusion pump pressure sensor (200 000 units per year);
- Catheter type pressure sensors;
- Lungs capacity meters;
- Kidney dialysis equipment;
- Human care support systems...

Other Applications

- Aerospace industry:
  - Pressure sensors for oil, fuel, transmission and hydraulic systems,
  - Airspeed measurements,
  - Safety devices (ejection seat control),
  - Navigation (gyroscopes).
- Consumer electronics:
  - Bicycle computers,
  - Scuba diving watches and computers,
  - Washers with water-level controls,
  - Smart toys.
- Military applications:
  - "Smart" weapons,
  - Impact and void detection,
  - Navigation and guidance systems,
  - Seismometry.
- Environmental applications:
  - Concentration of substances.
- Food industry:
  - Contaminants.
- Industrial products for:
  - Hydraulic systems,
  - Heating, ventilation and air conditioning systems,
  - Water level control.
- Robotics:
  - Distance, acceleration, force, pressure, temperature,
  - Position, tilt.

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Microsensors

- **MEMS** based devices (**M**icro-**E**lectro-**M**echanical **S**ystems):
  - A fabrication approach that enables the development of electromechanical systems using batch fabrication techniques similar to those used for *microelectronics*.
  - Integrates mechanical elements, sensors and actuators, and electronics on a common substrate.
  - MEMS generally range in size from a µm to a mm:
    - *Surface* effects such as electrostatics and wetting dominate *volume* effects such as inertia and thermal capacity.

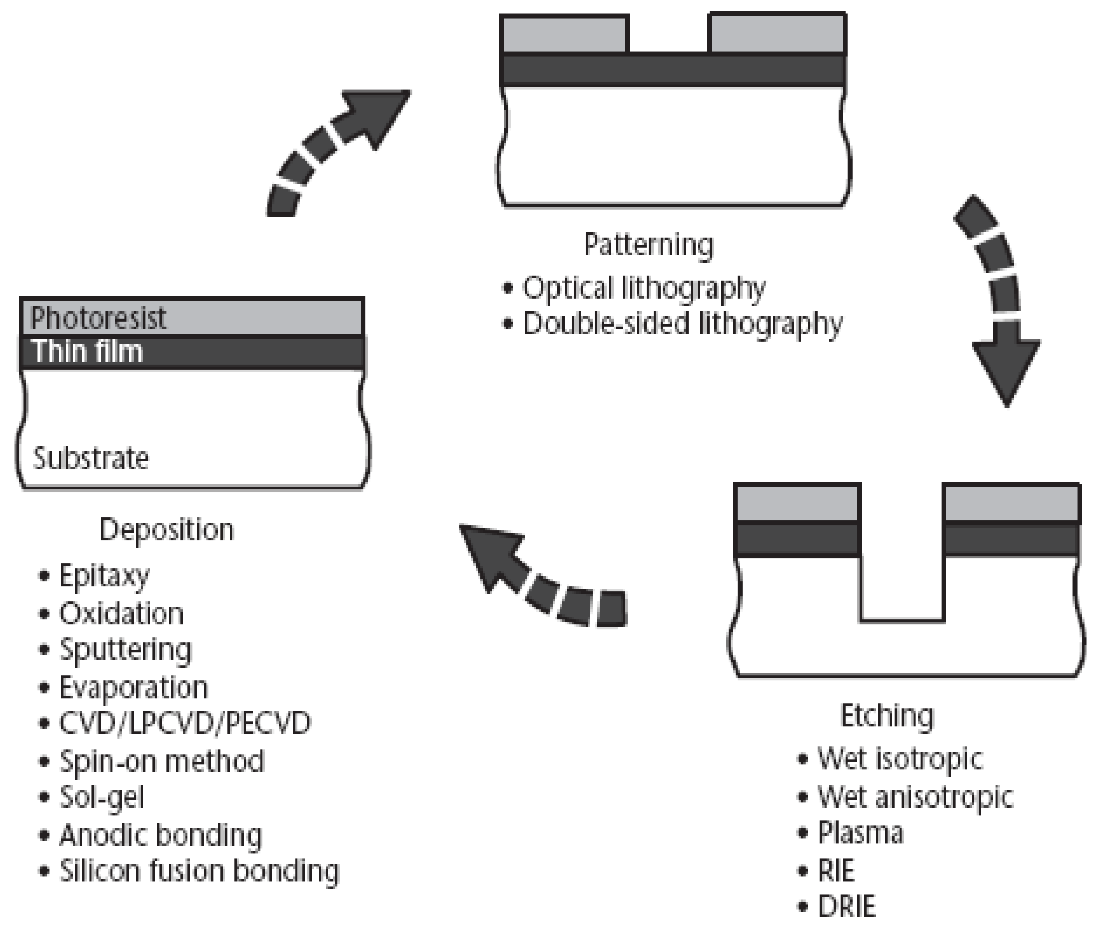
- Why microsensors?
  - Lower manufacturing cost (mass production, less material);
  - Exploitation of the IC technology;
  - Wider applicability to sensors arrays;
  - Lower weight (greater portability).

MEMS *vs.* Microelectronics

- **Materials:**
  - ME: Silicon and silicon compounds, metals;
  - MEMS: Silicon and silicon compounds, metals, polymers, glass, etc.
- **Functions:**
  - ME: Electrical;
  - MEMS: Electrical, mechanical, optical, chemical, biological, etc.
- **Structures:**
  - ME: Stationary, high density, 2D, isolated from environment;
  - MEMS: Stationary and movable, low density, 3D, interfaced with contacting media.
- **Maturity:**
  - ME: Mature design methodology, standardised, well documented;
  - MEMS: No design methodology, no standards, distinct techniques.

Basic Process Flow

- Layers are *deposited*.
- Photoresist is lithographically *patterned*.
- Underlying materials are *etched*.
- The process is *repeated* until completion of the microstructure.



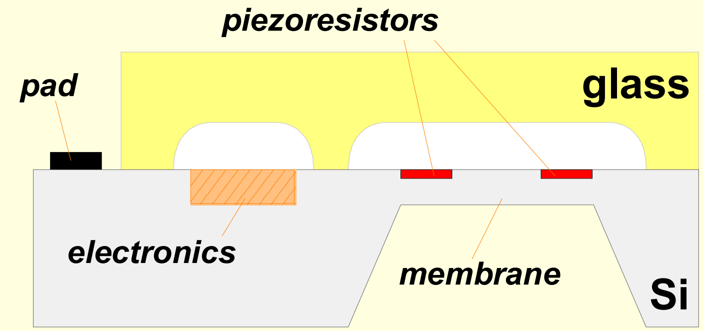
MEMS Processes

- **Photolithography**.
- **Implantations** and **Diffusions**.
- **Deposition** processes:
  - Oxidation;
  - Sputter deposition;
  - Physical and Chemical Vapour Deposition (PVD, CVD);
  - Electroplating.
- **Etching** processes:
  - Wet etching: isotropic or anisotropic;
  - Reactive Ion Etching (RIE);
  - Deep Reactive Ion Etching (DRIE).
- **Wafer Bonding**.

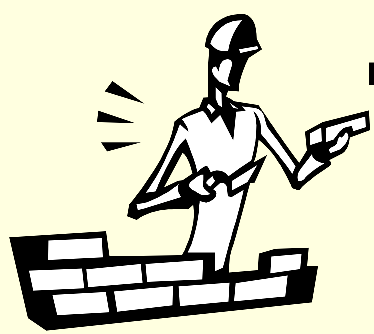
MEMS specific processes

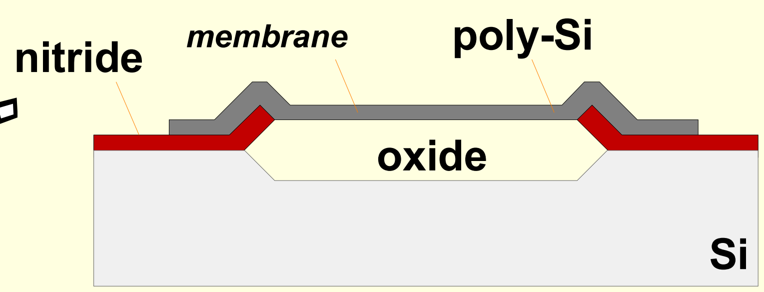
Micromachining Techniques

- **Bulk Micromachining** is a *process* that produces structures *inside* the substrate by selective etching.
  - **HARM-SOI** (**H**igh **A**spect **R**atio **M**icromachining **SOI**)



- **Surface Micromachining** is a *process* that creates structures *on top* of the substrate by film deposition and selective etching.



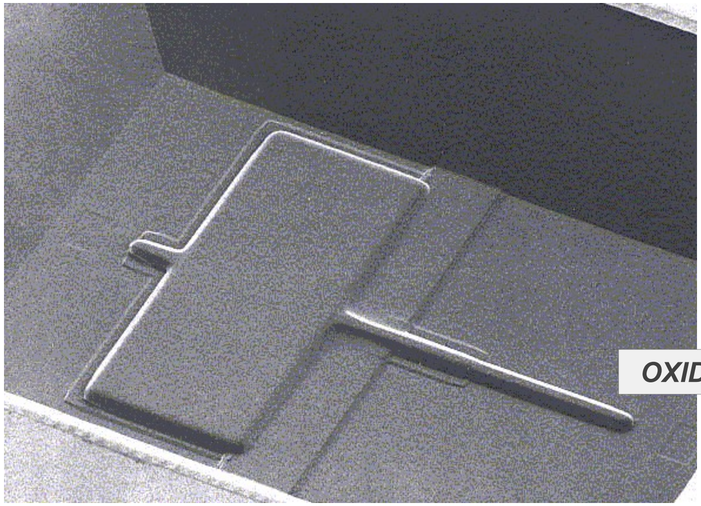


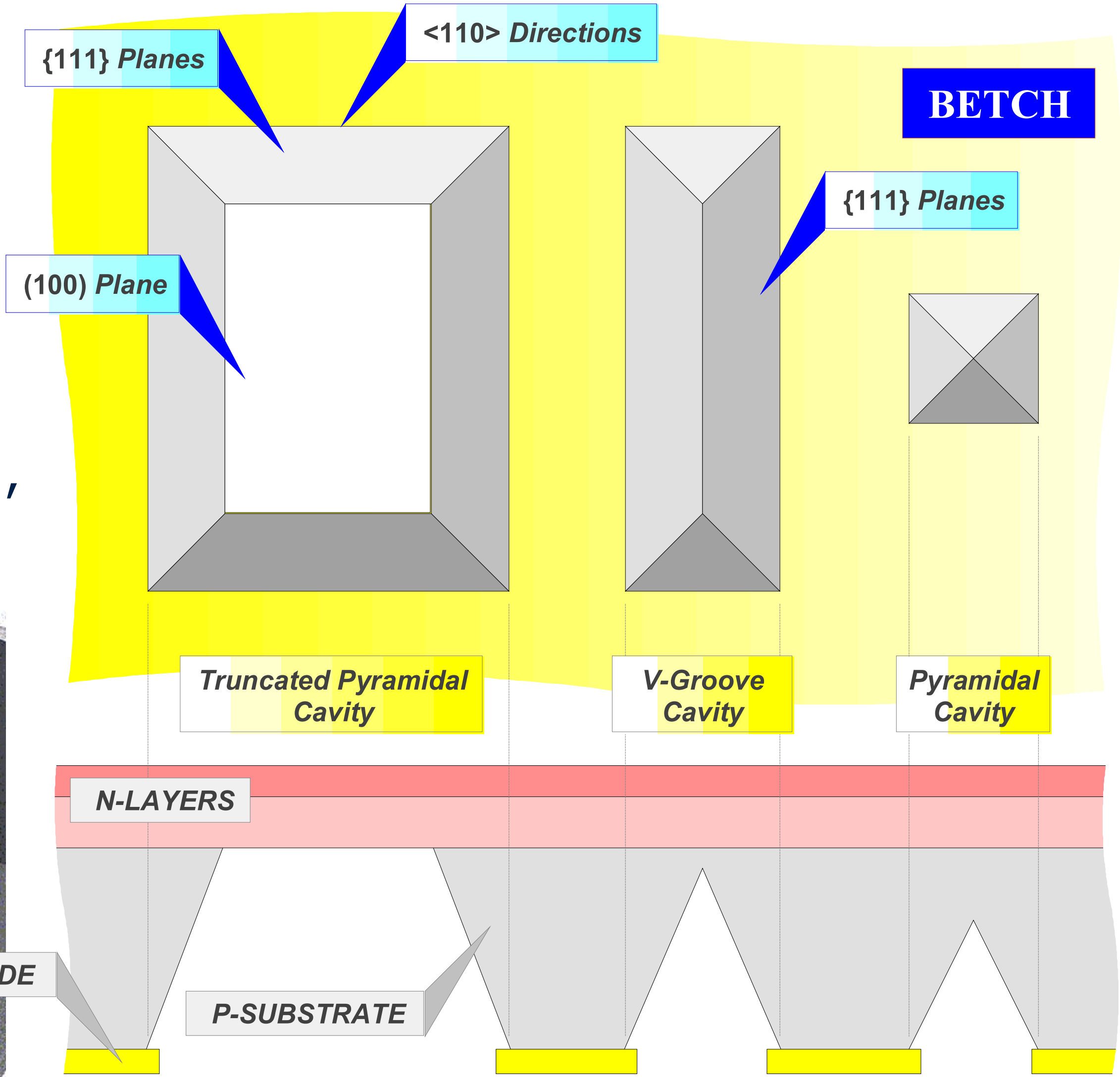
- **LIGA**

MultiMEMS

Wet Anisotropic Etching

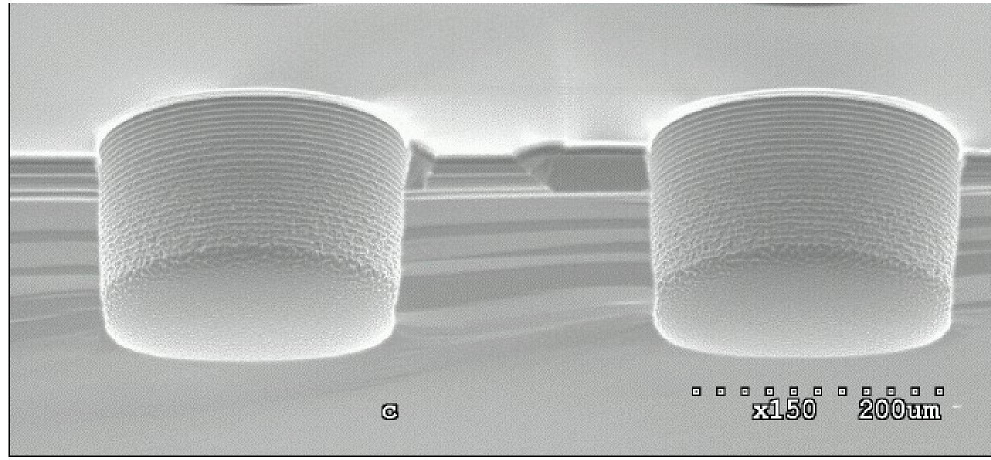
- Etchants:
  - EDP,
  - KOH,
  - TMAH.
- Etch-stop techniques:
  - Electrochemical (**ECES**),
  - Boron (**BES**).

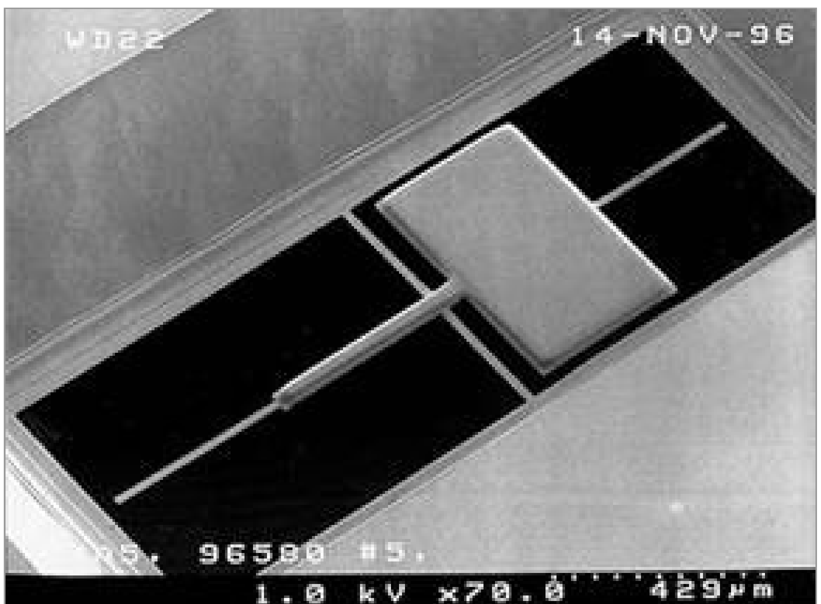


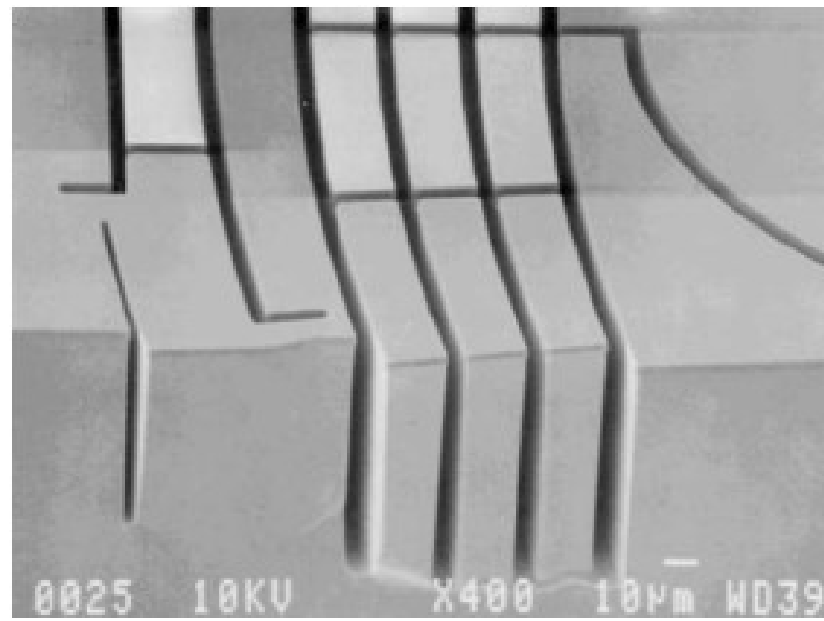


RIE and DRIE

- Chemical and physical, higly-selective etching.
- "Bosch" process.

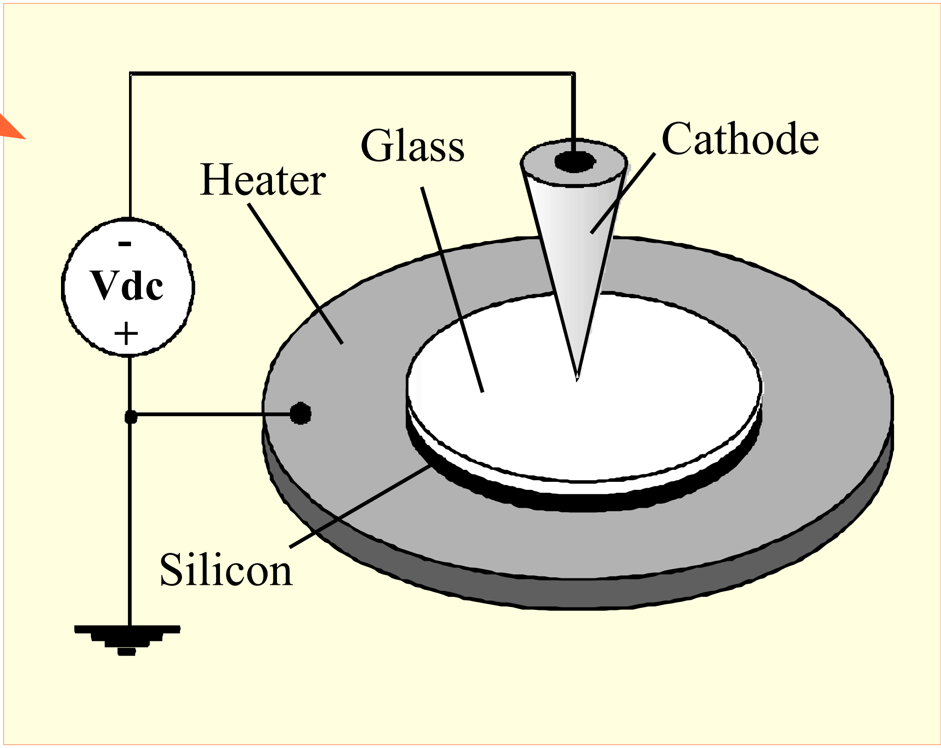






Wafer Bonding Techniques

- **Anodic bonding**.
- Direct bonding:
  - Fusion,
    - High temperature;
  - Plasma activated,
    - Low temperature.
- Eutectic bonding.
- Thermocompression bonding.
- Glass frit bonding.
- Epoxy bonding.



Trends in Sensors Technology

- **Miniaturization:**
  - Low size ➔ high volume ➔ low cost.
- **Integration** (sensor, signal processing, actuator)**:**
  - Sensors with signal processing circuits, (for linearization of the output, etc.);
  - Sensors with built-in actuator for self-test, automatic calibration, change of sensitivity…
- **Arrays of sensors:**
  - One-function units,
    - for improving reliability and
    - for achieving larger output signals.
  - Multiple function units.

General Requirements for a Sensor

- Low sensitivity to secondary inputs, such as:
  - Low temperature sensitivity,
  - Low off-axis sensitivity;
- Linearity;
- Long-term stability;
- Low pressure and temperature hysteresis;
- Small size, low cost;
- Hermeticity;
- Resistance to corrosive ambients;
- Biocompatibility with the body...

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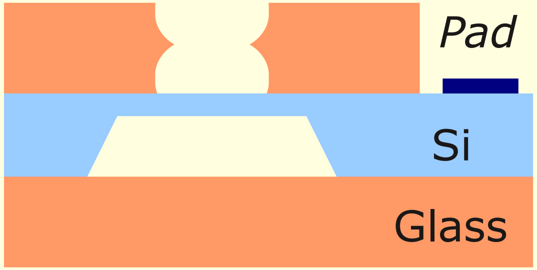
Pressure Sensors Designs

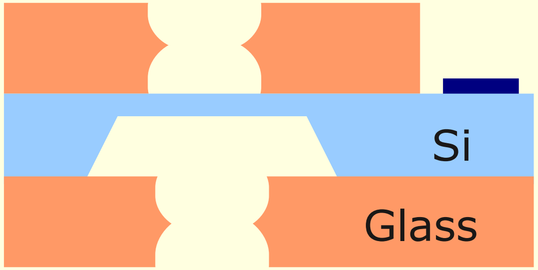
Absolute Pressure Sensors

Bottom inlet

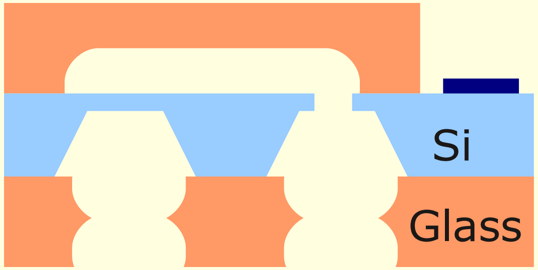


Top inlet

Relative Pressure Sensors



Top and bottom inlets



Bottom inlets

Top inlets

MultiMEMS

Pressure Sensors: Sensing Principles

- **Piezoresistive:**
  - Deformation → Stress → Resistance change.
- **Capacitive:**
  - Deformation → Displacement → Capacitance change.
- **Resonant:**
  - Deformation → Stress → Resonance frequency change.
- **Optical:**
  - Deformation → Phase change → Interference pattern.
- **Thermal:**
  - Thermal conductivity change between a heat source and heat sink.
- **Piezo-junction effect:**
  - Deformation → Stress → Junction internal potential.

Outline

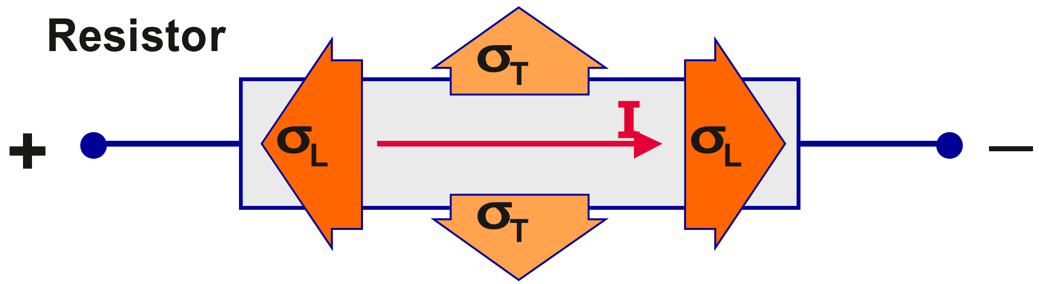
Piezoresistive Effect

- Change of *electrical resistance* due to applied *mechanical stress*.

Coeffiecients of piezoresistivity

$$R = R_0 \cdot (1 + \Pi_L \cdot \sigma_L + \Pi_T \cdot \sigma_T)$$

Relative to the flow of the electric current



The structures are typically designed such that the principal in-plane stress is along the resistor axis.

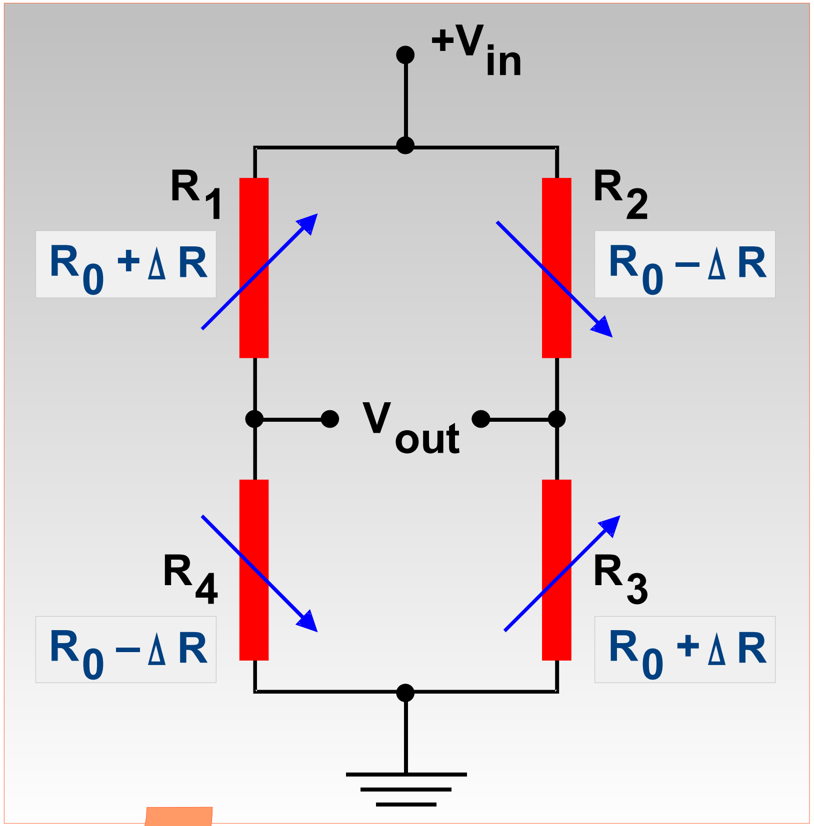
Wheatstone Bridge

- Converts the *resistance change* into *voltage output*.

$$V_{out} := V_{in} \cdot \frac{\Delta R}{R_0}$$

Linear with ΔR.
No first order temperature and non-linearity effects.

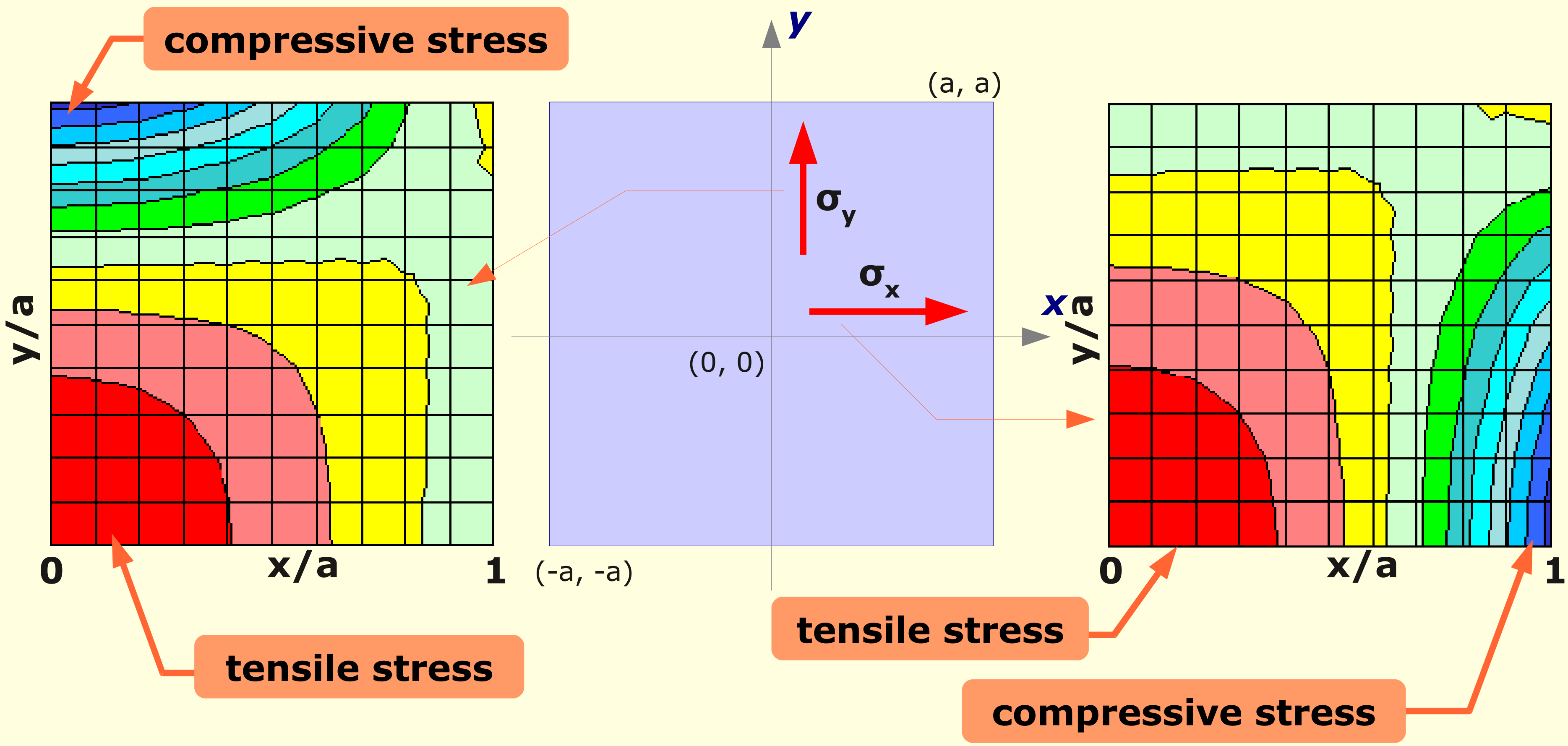
$$V_{out} := V_{in} \cdot \left(\frac{R_1}{R_1 + R_4} - \frac{R_2}{R_2 + R_3} \right)$$



Pressure causes stress in the membrane, thus resistance changes.

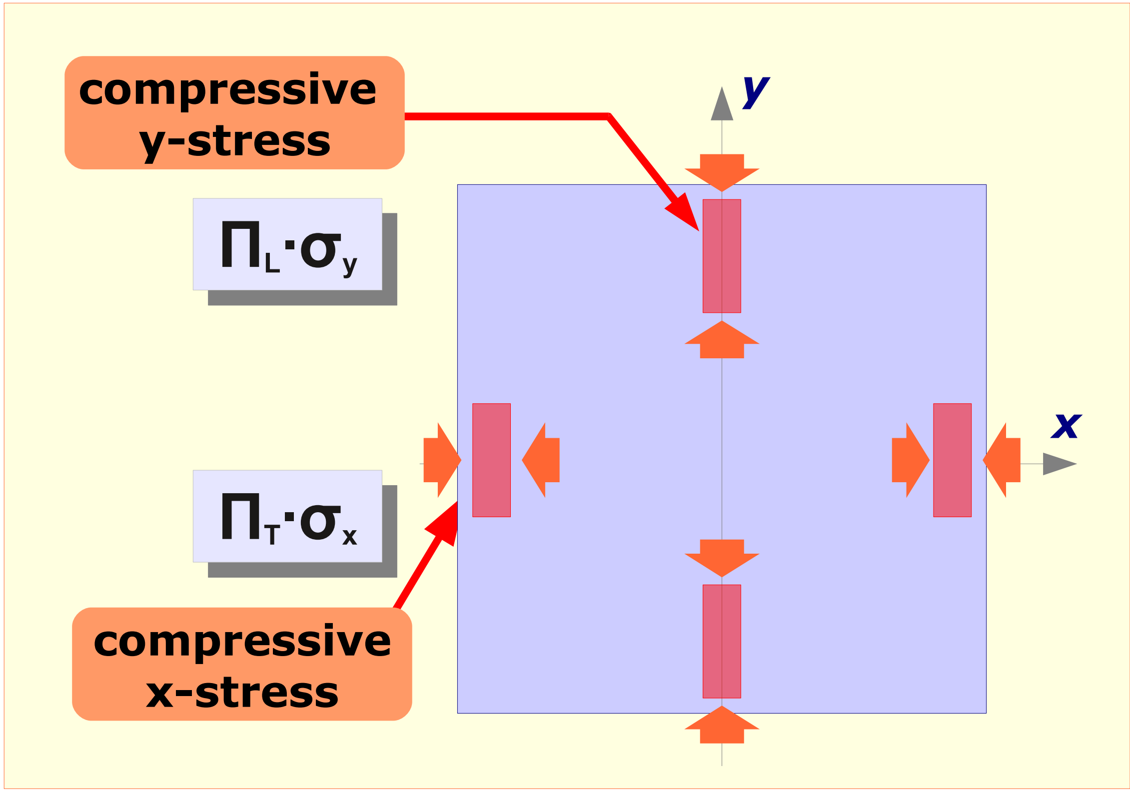
Stress in Square Membranes

- Mechanical stress in a clamped, square silicon membrane subjected to an uniform pressure:



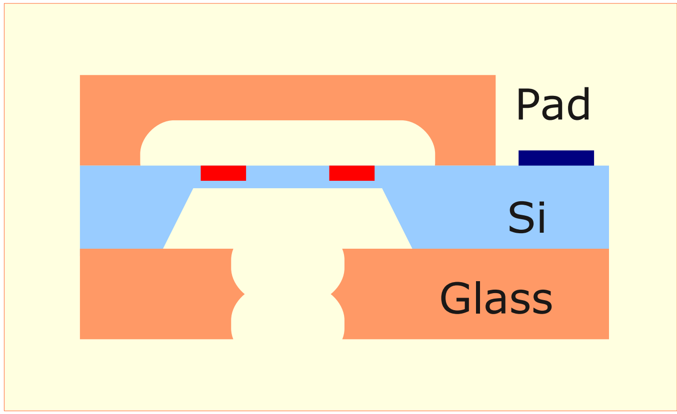
Placement of Resistors

- Criteria:
  - Sensitivity (locations with high stress values);
  - Non-linearity effects;
  - Process tolerances;
  - Off-set;
  - Pacakage stress.



Sensitivity to Process Variations

- Membrane thickness.
- Membrane size.
- Alignment between membrane and resistors.



- Resistors size:
  - Perpendicular resistors extend away from the edge;
    - *Example*: For a 100 μm long resistor on 1 mm x 1 mm membrane, the average stress is 60% of the value at the edge.
  - Parallel resistors must be placed at a certain distance from the edge to guard against alignment errors.
- Resistors matching (lithography effects).
- Membrane taper (non-uniform thickness);
  - Small effect on sensitivity for membranes thicker than 10 μm.

Sources of Temperature Drift

Temperature coefficient of sensitivity, TCS: $$TCS = \frac{1}{S} \cdot \frac{\partial S}{\partial T}$$

Temperature coefficient of off-set, TCO: $$TCO = \frac{1}{V_{dd}} \cdot \frac{\partial V_{out}|_{P=0}}{\partial T}$$

- Temperature dependence of the piezoresistive coefficients.
- Gas expansion in the reference cavity (if present).
- Resistors tracking errors.
- Junction leakage currents.
- Thermally induced stress at the Si-insulator interface.
- Packaging effects.

Sources of Non-Linearity

- Non-linearity of the mechanical stress with the applied pressure (the balloon effect);
  - Can be reduced by local stiffening of the membrane, but at the expense of miniaturization.
- Misbalance of the Wheatstone bridge;
  - Can be reduced by design and good process control.
- Non-linearity of piezoresistive effect:
  - Depends on the crystallographic orientation (larger non-linearity for the directions with larger Π coefficients);
  - Depends on temperature.

Bulk *vs.* Surface Micromachined Piezoresistive Pressure Sensors

- Single Crystal Silicon
  - Few defects;
  - Repeatable mechanical properties;
  - Larger piezoresistive gauge factor.
- Polysilicon Films:
  - Mechanical properties strongly varying with the processing conditions;
  - Compressive or tensile stress present in the films;
  - Smaller piezoresistive gauge factor.

Parameter	SM	BM
Mechanical properties	Good	Superior
Cost, low volume	Fair	Good
Cost, high volume	Good	Fair
Dimensional control	Better	Good
CMOS integration	Good	Fair
Packaging	Fair	Fair
Size	Smaller	Small

BM parts appear to be more sensitive to package stress.

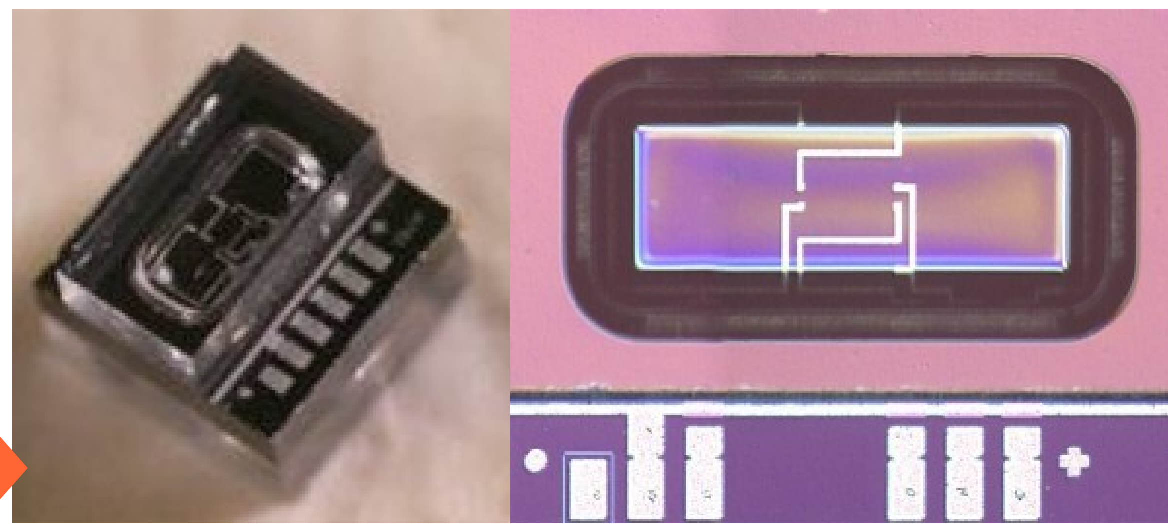
SM parts are smaller.

In general, better performances for **BM** sensorss, except for TCS and TCO (caused by the non-optimal stress isolation of the **BM** dice from the package).

SensoNor's Pressure Elements

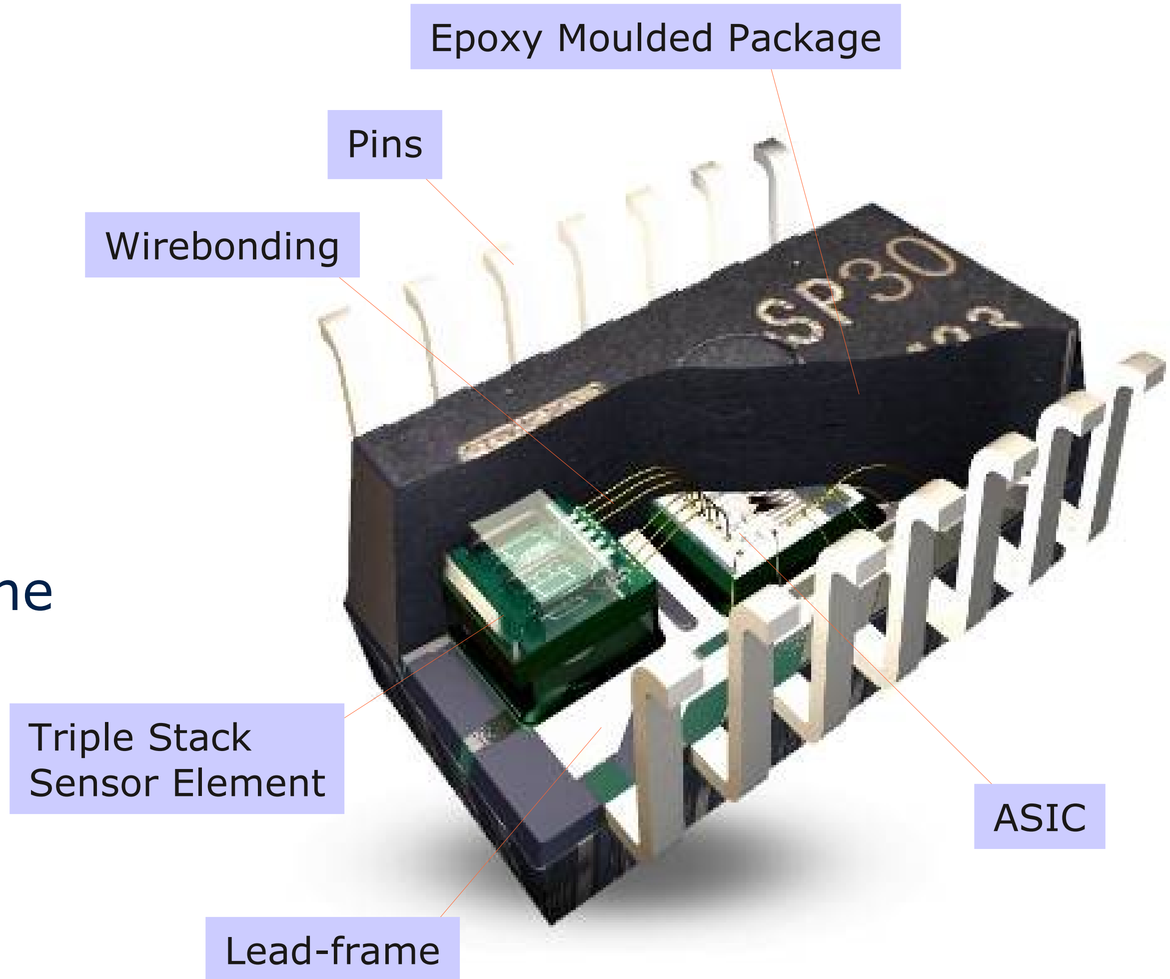
- Key features:
  - High stability *buried piezoresistors*;
  - High precision membrane definition
(by anisotropic wet etching and electrochemical etch-stop);
  - Hermetically sealed cavities with electrical feed-throughs
(by triple-stack *anodic bonding*).

Absolute pressure sensors.
SensoNor Technologies AS.



SensoNor's TPMS

- SW412 sensor element:
  - Pressure sensor;
  - Accelerometer (to detect rolling).
- SP30-type ASIC:
  - ADC;
  - µ-controller.
- Assembly on lead-frame in an SOIC-package.

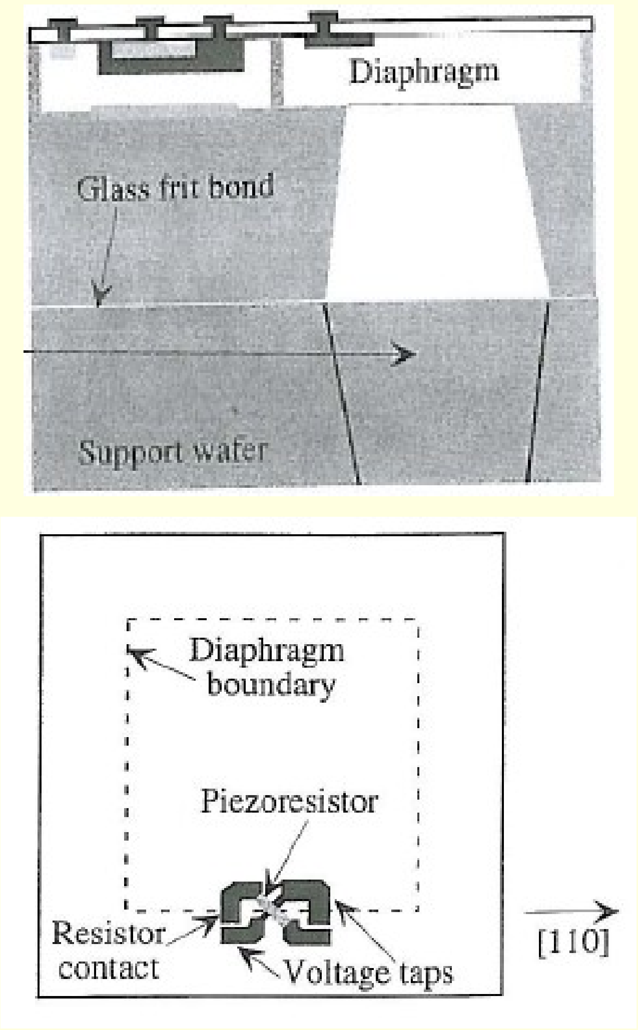


MultiMEMS

Motorola's Pressure Elements

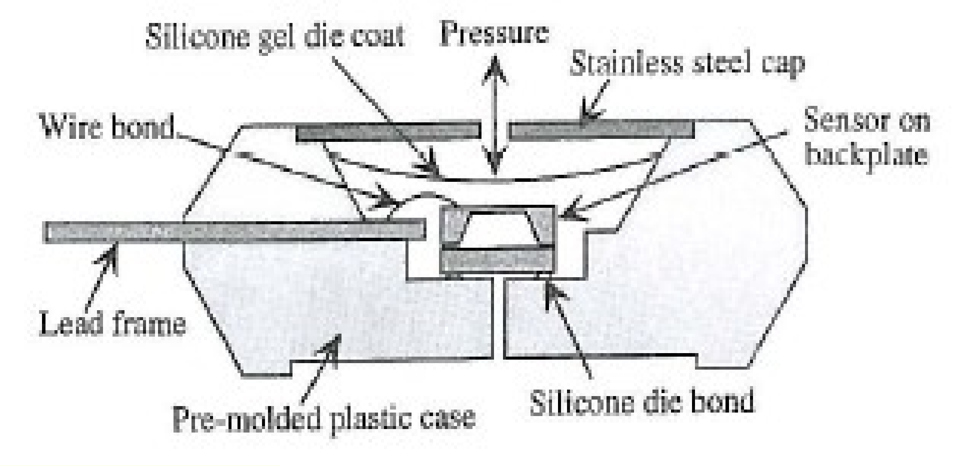
- Key features:
  - *Fully integrated* (bipolar transistors for the on-chip circuitry);
  - Optimized bipolar process for (100) wafers;
  - Single, low doped piezoresistor, oriented at a 45º angle to the side of the square membrane;
  - CrSi alloy *trimmed* resistor contacts;
  - Wet anisotropic etching with electrochemical etch-stop;
  - Silicon-silicon *glass frit bonding*.

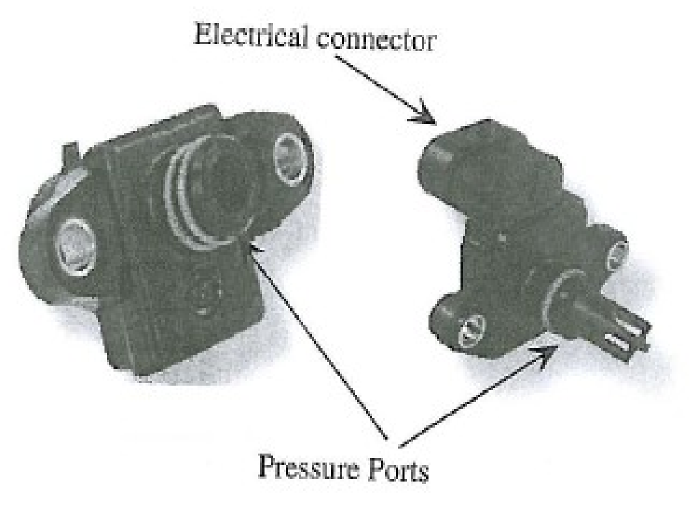
Absolute pressure sensor. Motorola, Inc.



Motorola's MAP Sensor

- Key features:
  - Wafer-level sealing with glass frit;
  - Die bond with low stress silicone gel;
  - Pre-molded package;
  - Wire bonding to a lead frame;
  - Silicone gel for protection against ambient;
  - Stainless steel cap.

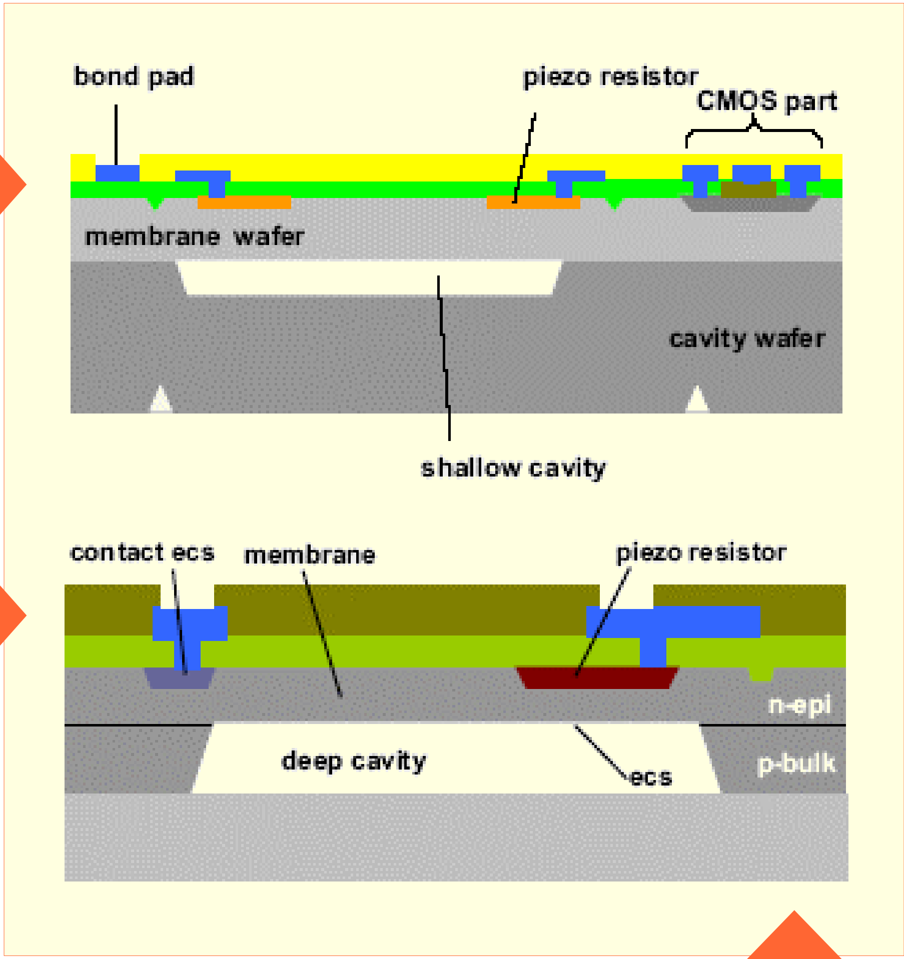




Packed manifold absolute pressure (MAP) sensor. Motorola, Inc.

X-Fab's Pressure Sensors

- On pre-processed substrates:
  - *Fusion bonding*;
  - High temperature annealing;
  - Thinning;
  - Si-piezoresistors;
  - *Fully integrated* (CMOS process).
- On backside sealing of a relative pressure sensor:
  - Sensor processing, including wet anisotropic etching with electrochemical etch stop;
  - Si-piezoresistors;
  - Low temperature *plasma activated bonding*.

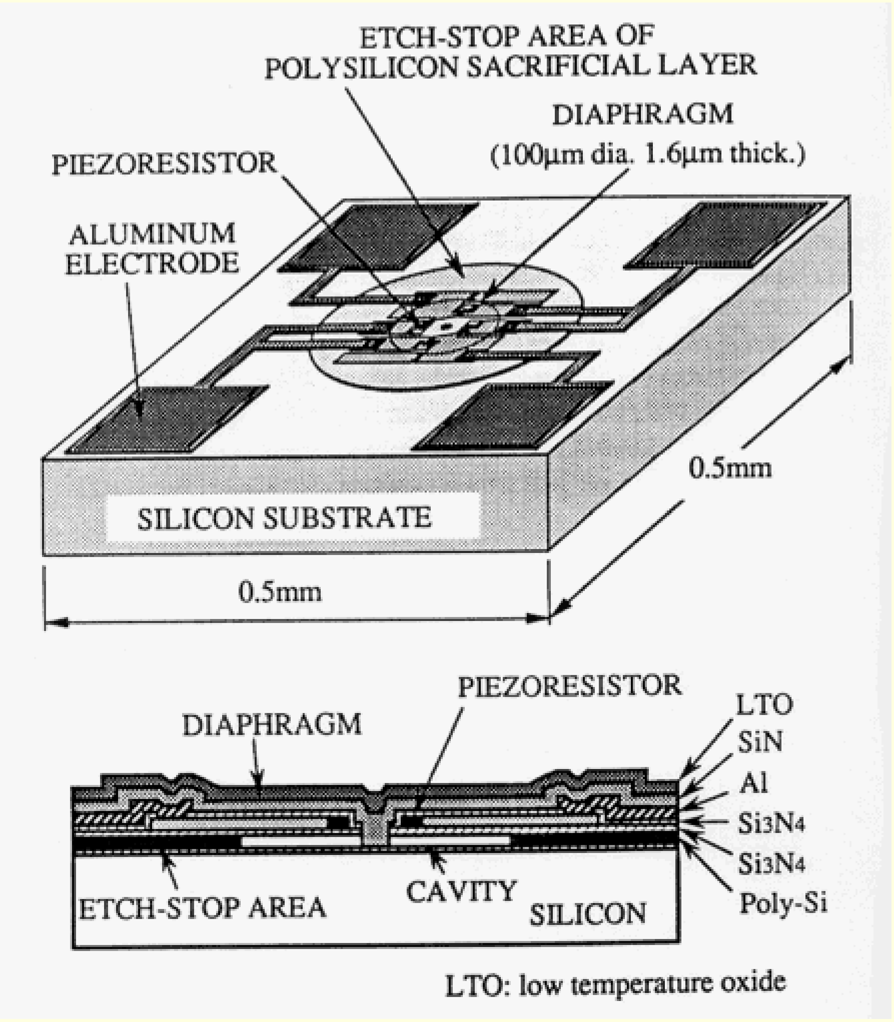


Absolute pressure sensors.
X-FAB Semiconductor Foundries.

Toyota's Pressure Sensors

- Key features:
  - Silicon nitride diaphragm;
  - *Polysilicon piezoresistors*;
  - Surface micromachined;
  - Electronics can be integrated on the same die;
  - 32x32 array and electronics, suitable for tactile sensing.

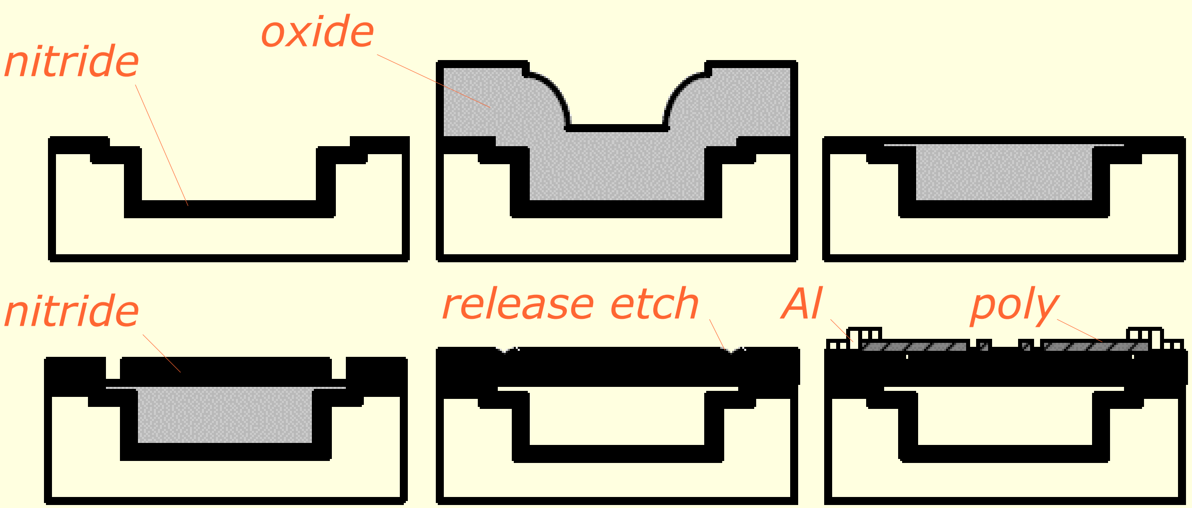
Absolute pressure sensor.
Toyota Central R&D Laboratory, Inc.

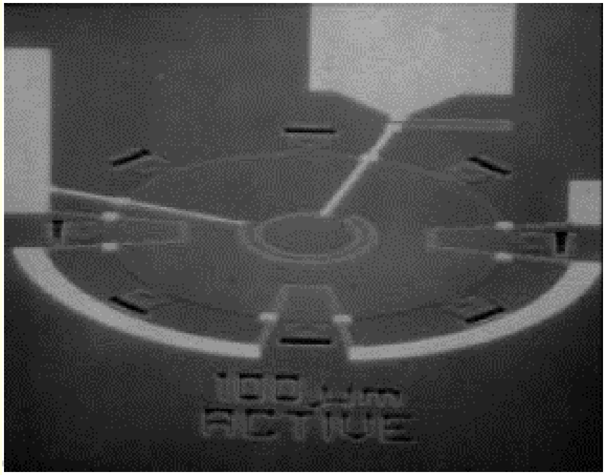


Sandia's Pressure Sensor

- Key features:
  - Low-stress silicon nitride or polysilicon diaphragms, with clamped edges;
  - *Polysilicon piezoresistors*;
  - Entirely CMOS compatible process;
  - Stiction may occur for diaphragms larger than 250 μm diameter.

Absolute pressure sensors.
Sandia National Laboratories.





Outline

Capacitive Sensing Principle

- Change of *capacitance* caused by *displacement*.

$$C_0 = \frac{\varepsilon_0 \cdot \text{Area}}{d_0}$$

$$C = \epsilon_0 \cdot \iint_{Area} \frac{dx \cdot dy}{d_0 - w_{x,y}}$$

$$\Delta C \sim P_{ext}$$

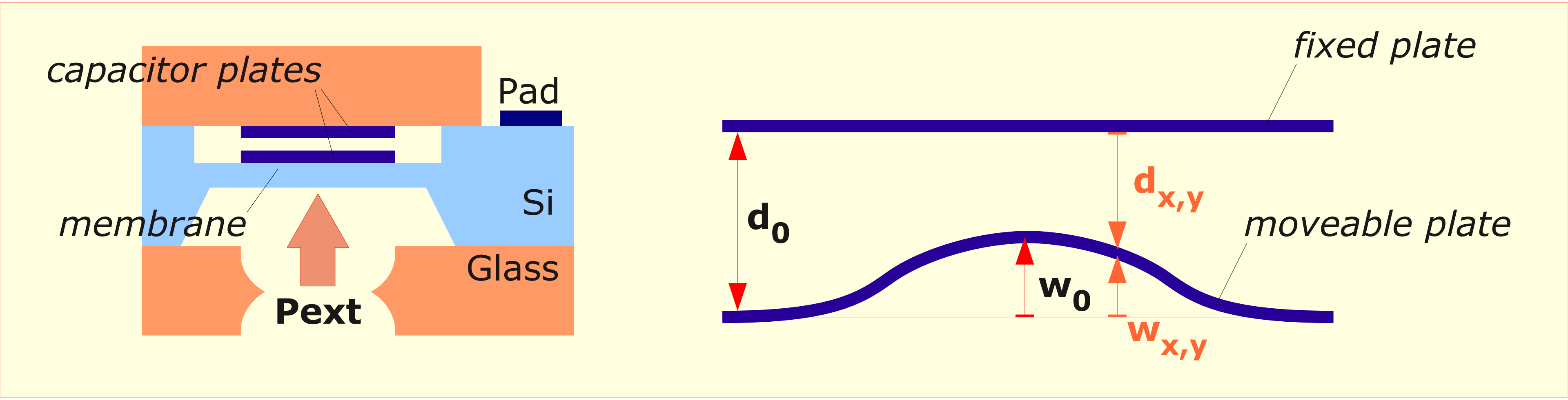
free space permittivity

original gap

gap at (x, y)

deflection at (x, y)

external pressure



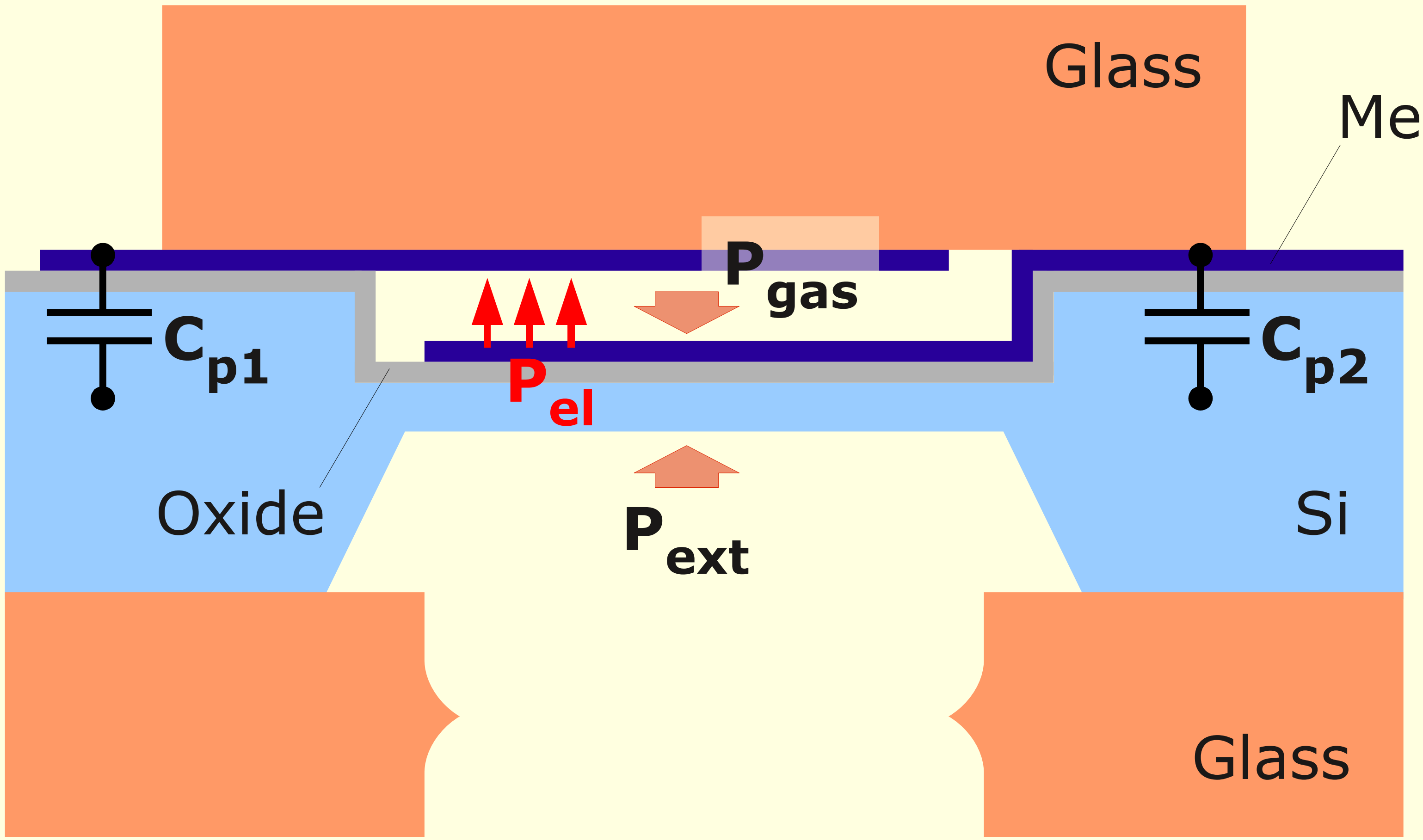
Capacitive Sensing Trade-offs

- Advantages:
  - Larger dynamic range;
  - Lower temperature coefficients;
  - Lower power consumption.
- Drawbacks:
  - Nonlinear response to the applied pressure,
    - Difficult sensor compensation;
  - Somewhat more difficult process:
    - Control of gap (warp, bending, etc.),
    - Stiction;
  - Larger die area;
  - Parasitic (stray, insulating) capacitances;
  - Trade-off between dynamic range, linearity and absolute sensitivity.

Sources of Errors

- Non-linearity of the response to the applied pressure.
- Parasitic capacitances:
  - Usually of the same order of magnitude as the sensing capacitance, few pF.
- The electrostatic pressure:
  - Systematic error (important if the voltage is high and the pressure range small),
  - Failure of the sensor if collapse occurs.
- Trapped gas compression, $P_{ref} = f\,(P_{ext})$:
  - Decreased sensitivity,
  - Increased non-linearity,
  - Large temperature drift.
- Residual stress in membrane (intrinsic or/and caused by thermal mismatch):
  - Tensile stress ➔ Increased stiffness ➔ Decreased sensitivity
  - Compressive stress ➔ Buckling ➔ Device failure.

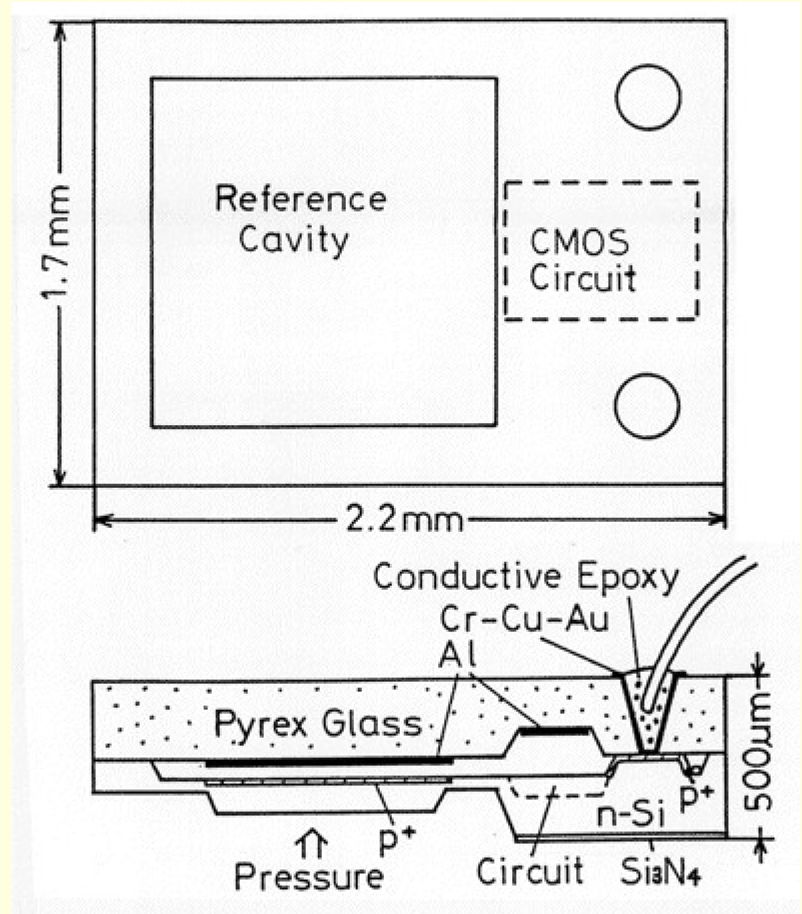
Sources of Errors Illustrated



Tohoku's Pressure Sensor

- Key features:
  - Bulk micromachined device;
  - Wet anisotropic etching;
  - Glass-silicon-glass anodic bonding;
  - Non-evaporable *getter* for low cavity pressure;
  - *Vertical feed-throughs*;
  - Electronics can be integrated on the same die.

Absolute pressure sensor.
Esashi *and co.*, Tohoku Univ.

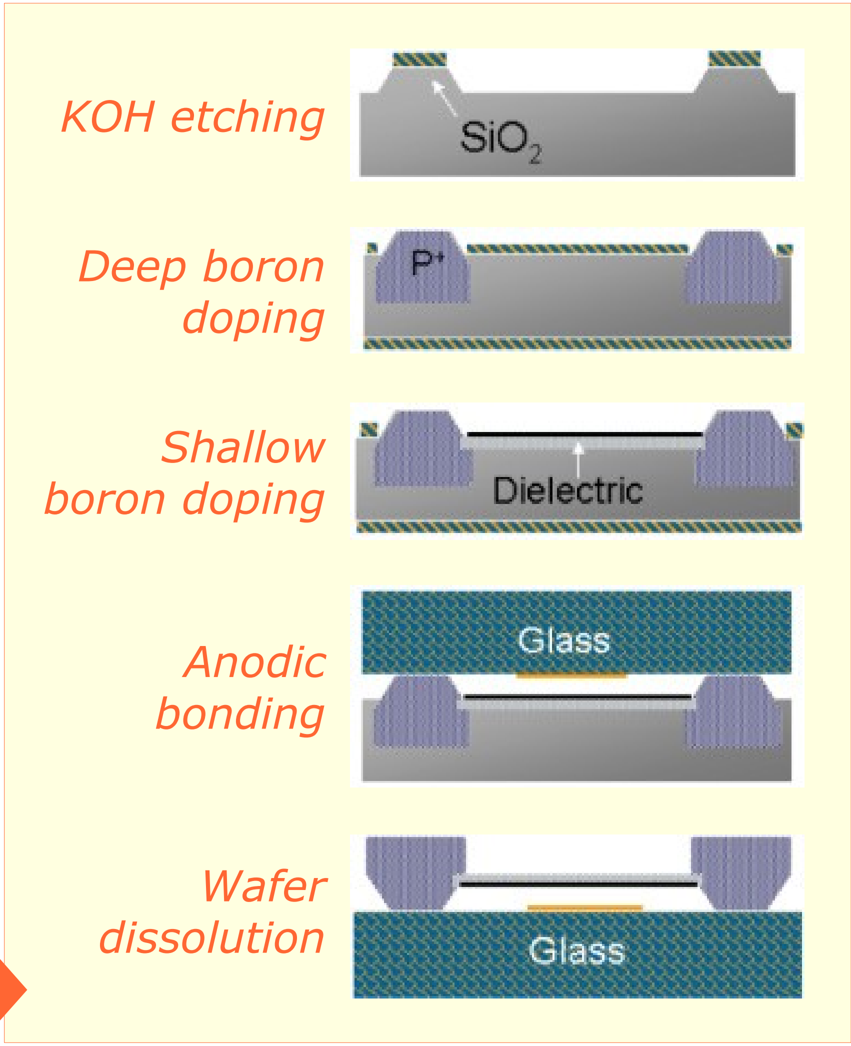


MultiMEMS

ISSYS' Pressure Sensor

- Key features:
  - *Dissolved wafer* process;
  - Single-crystal silicon microstructures on glass substrates;
  - Challenging electrical interconnection between the cavity and the outside (ISSYS patent).

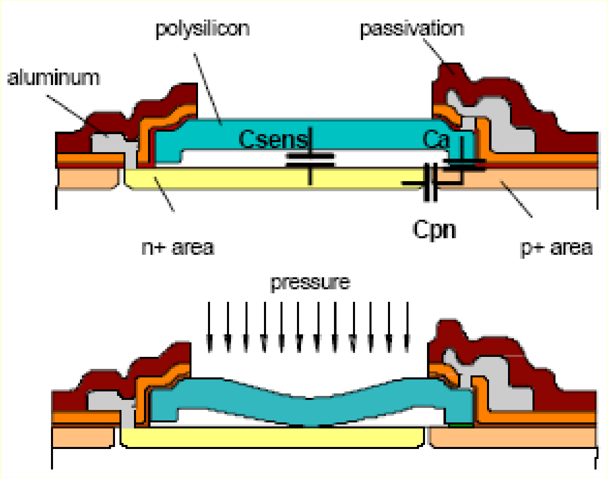
Absolute pressure sensor.
Integrated Sensing Systems, Inc.



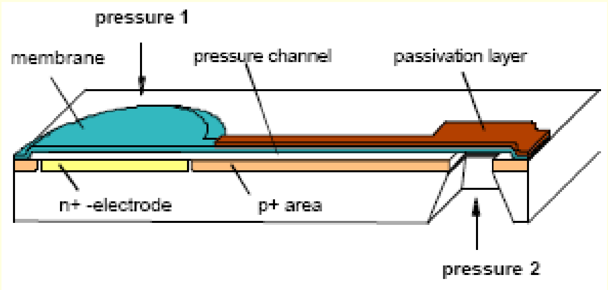
- Key features:
  - Surface micromachined *array* of capacitors array;
  - Range: 1 bar up to 350 bars sensors, absolute or relative;
  - High overpressure stability;
  - Low temperature dependency (reference cell used);
  - Low power consumption;
  - Small chip size;
  - *Monolithic ASIC integration*;
  - Extended temperature range for the SOI version.

Absolute and relative pressure sensors.
Fraunhofer IMS, Duisburg.

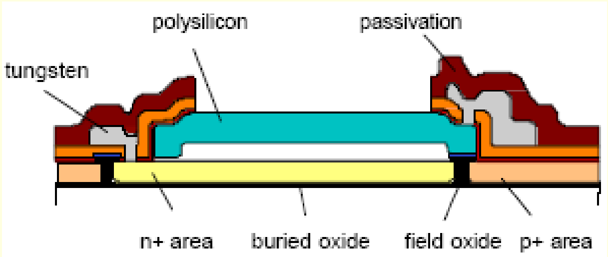
Microplate capacitors



Differential pressure sensor



SOI-based pressure sensor



MultiMEMS

Outline

Resonance Sensing Principle

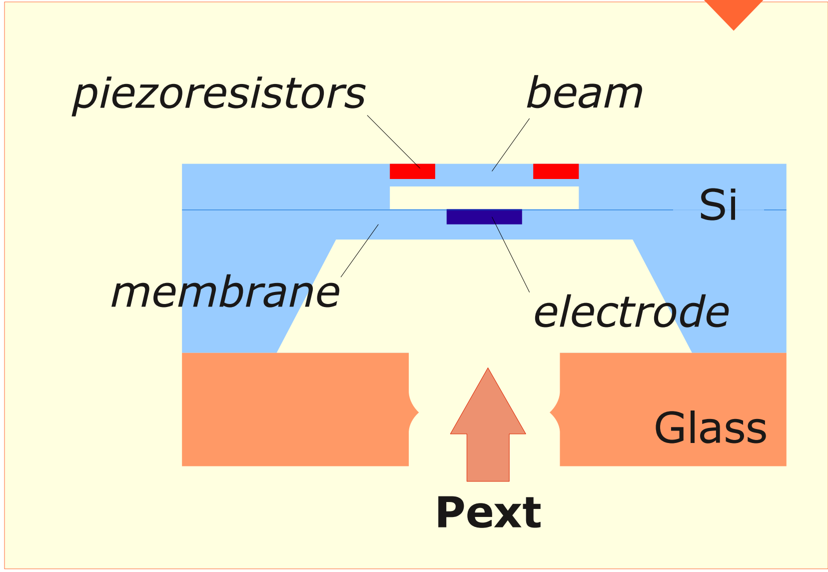
- The *resonance frequency* of a vibrating microstructure depends on the *mechanical stress*.
- Advantages:
  - The frequency output allows easy coupling to digital electronics: ➔ high precision measurements ➔ high resolution;
  - Requires only relative voltage level or phase shift measurements ➔ more immune to interferences;
  - Frequency is not dependent on electrical signals (unstable), but rather on mechanical properties ➔ long term stability;
  - Very low temperature errors (several orders of magnitude lower).
- Drawbacks:
  - Requires an excitation technique to initiate oscillations;
  - Mechanical damping is critical;
  - Inherently nonlinear ➔ more calibration points required.

Petersen's Resonant Pressure Sensor

- Key features:
  - Diaphragm with *embedded microbeam*;
  - Bulk micromachining;
  - *Fusion* and *anodic bonding*;
  - *Electrostatic excitation*;
  - *Piezoresistive detection*.

- Principle:
  - External pressure...
    ➔ tensile stress in the beam...
    ➔ change of resonance frequency...
    ➔ supply voltage adjustment
    required to keep the beam vibrating
    in the new state.

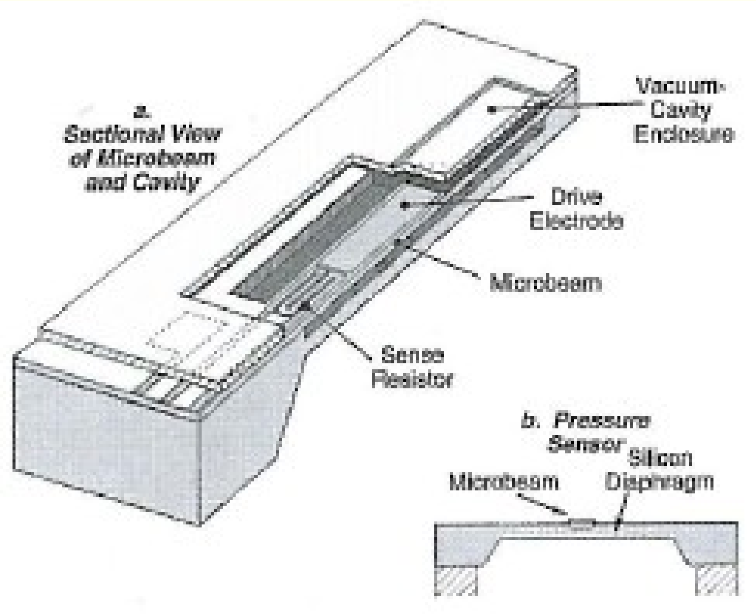
Resonant pressure sensor.
Kurt Petersen, IEEE Solid-State Sensor and Actuators Workshop, 1988.



MultiMEMS

Wisconsin's Resonant Pressure Sensor

- **Key features:**
  - Diaphragm with *embedded microbeam*;
  - Surface micromachining;
  - *Electrostatic excitation*;
  - *Piezoresistive detection*.

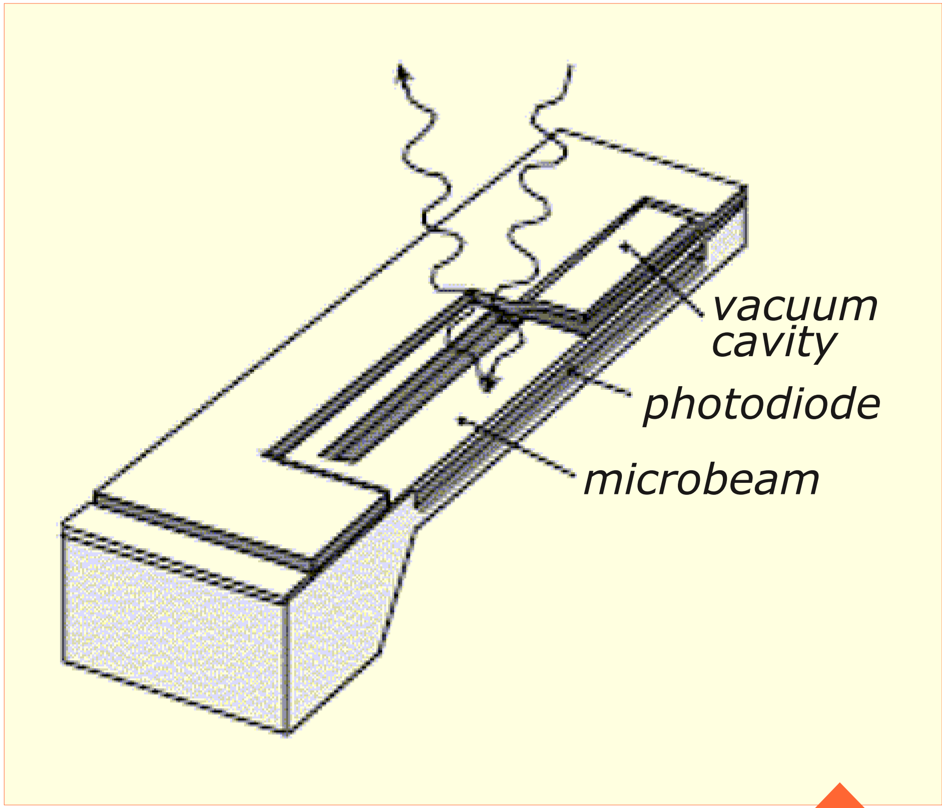


Absolute resonant pressure sensor. University of Wisconsin.

- **Principle:**
  - External pressure...
    → tensile stress in the beam...
    → change of resonance frequency...
    → supply voltage adjustment required to keep the beam vibrating.
  - Capacitive detection *cannot* be used (small sense capacitance compared to parasitics).

Honeywell's Optical Pressure Sensor

- Key features:
  - Diaphragm with *embedded microbeam*;
  - Surface micromachining;
  - *Optical excitation* (*pn*-junction laser through optical fiber);
  - *Optical detection*.
- Principle:
  - External pressure...
    ➔ tensile stress in the beam...
    ➔ change of resonance frequency...
    ➔ reflectivity change of the Fabry-Pérot cavity...
    ➔ modulation of the reflected light.



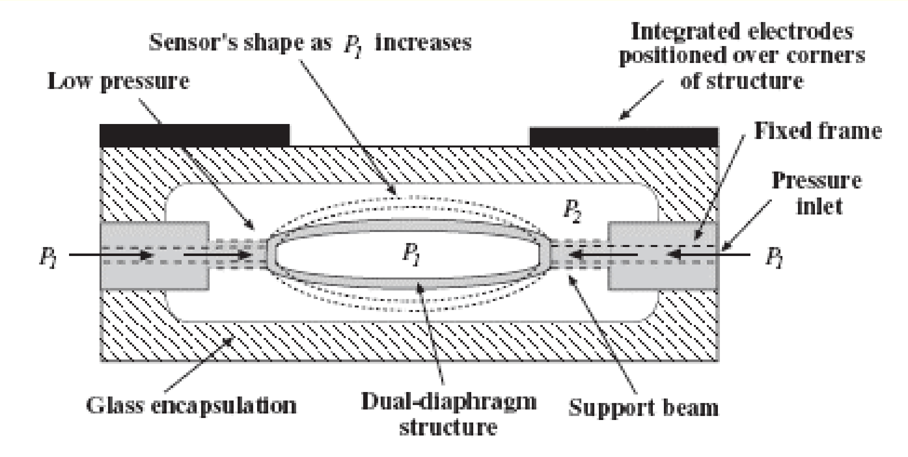
Optical pressure sensor.
Honeywell International Inc.

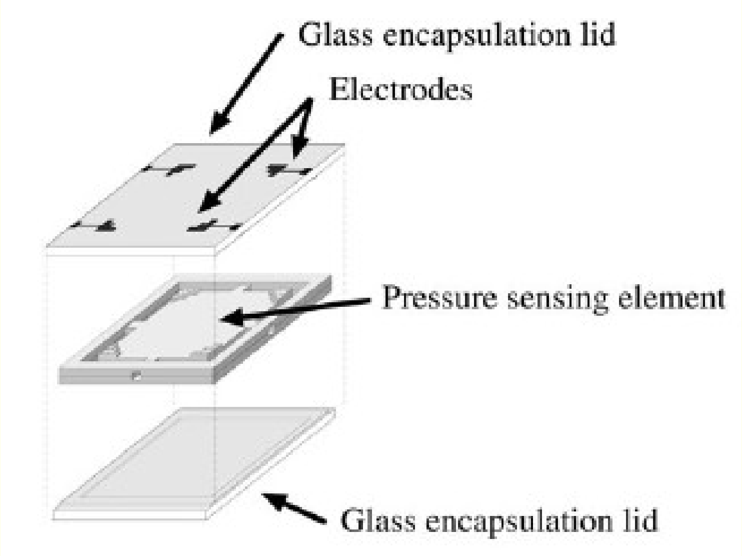
KTH's Resonant Pressure Sensor

- Key features:
  - *Dual diaphragm* device;
  - *Fusion* and *anodic bonding*;
  - *Electrostatic excitation*;
  - *Capacitive detection*;
  - Pressure to be measured inside the capsule.

- Principle:
  - External pressure...
    ➔ change of shape and stiffness of diaphragms...
    ➔ change of resonance frequency.

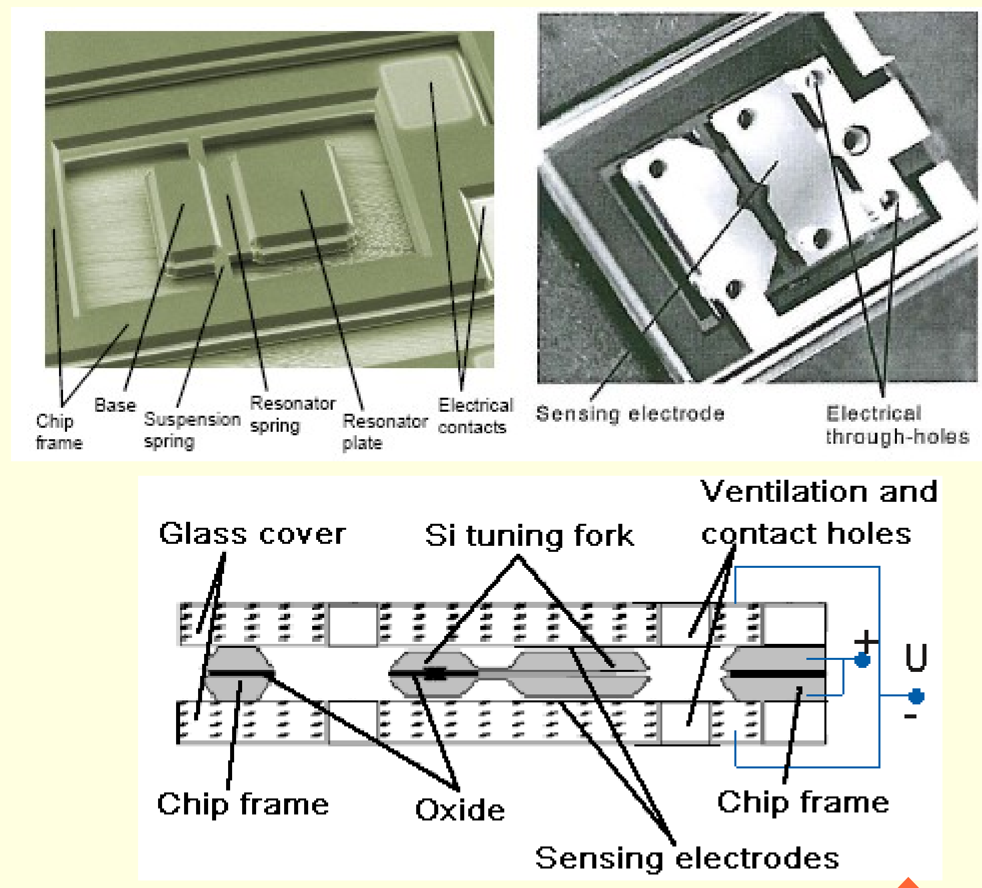
Absolute/relative pressure sensor.
KTH, Royal Institute of Technology.





Fraunhofer's Tuning Fork

- Key features:
  - Bulk micromachining;
  - *Fusion bonding*;
  - *Electrostatic excitation*;
  - *Capacitive detection*;
  - Ultrasonic *drilling* of holes in glass for ventilation and electrical contacts;
  - *Shadow mask* technology for selective Al deposition.
- Principle:
  - External pressure...
    ➔ change of gas viscosity...
    ➔ change of resonance frequency.



Absolute pressure sensor. Fraunhofer Institute and University of Chemnitz.

Outline

MultiMEMS

Definitions

- Mechanical sensitivity, $\mathbf{S_z}$:

$$z = S_z \cdot F_z \qquad S_z = 1/k_z$$

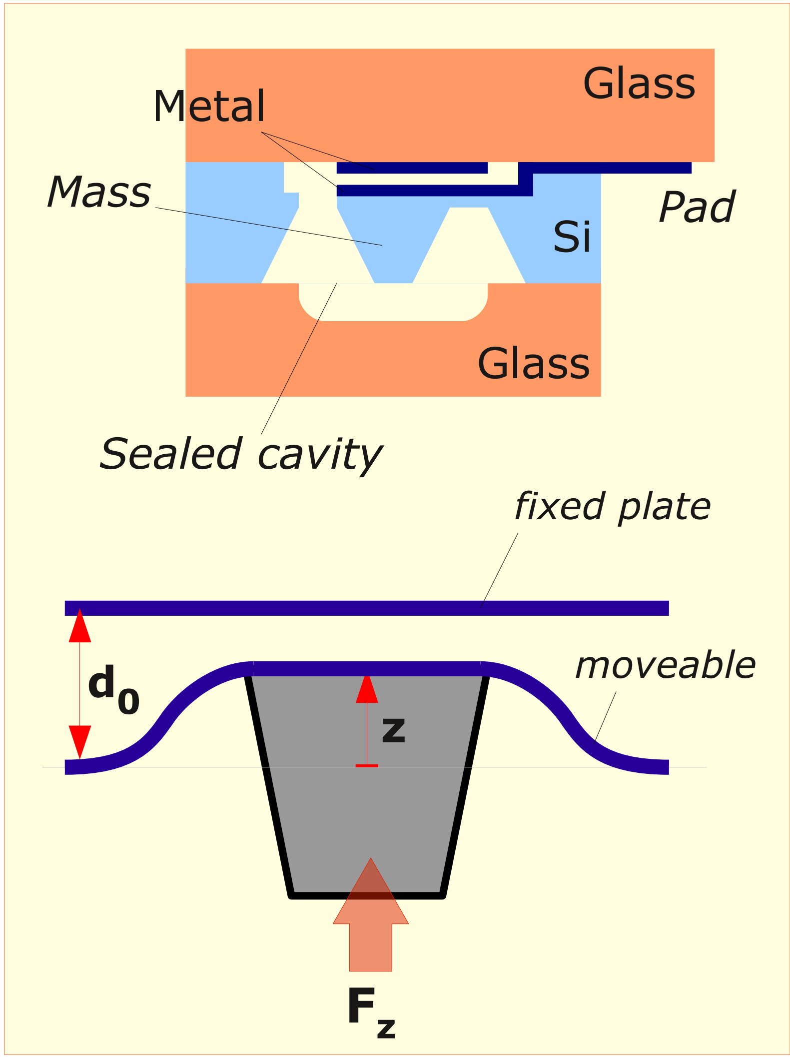
Displacement — Input signal — Elastic constant

- Electrical sensitivity, $\mathbf{S_e}$:

$$V_{out} = S_e \cdot F_z$$

Output signal

- Frequency band:
  - The domain in which the input acceleration can be still measured correctly by the accelerometer;
    - Strongly related to the natural resonant frequency of the mechanical system.



Mass-Spring System

$$M\cdot\frac{d^2x}{dt^2} = M\cdot a - k\cdot x - D\cdot\frac{dx}{dt}$$

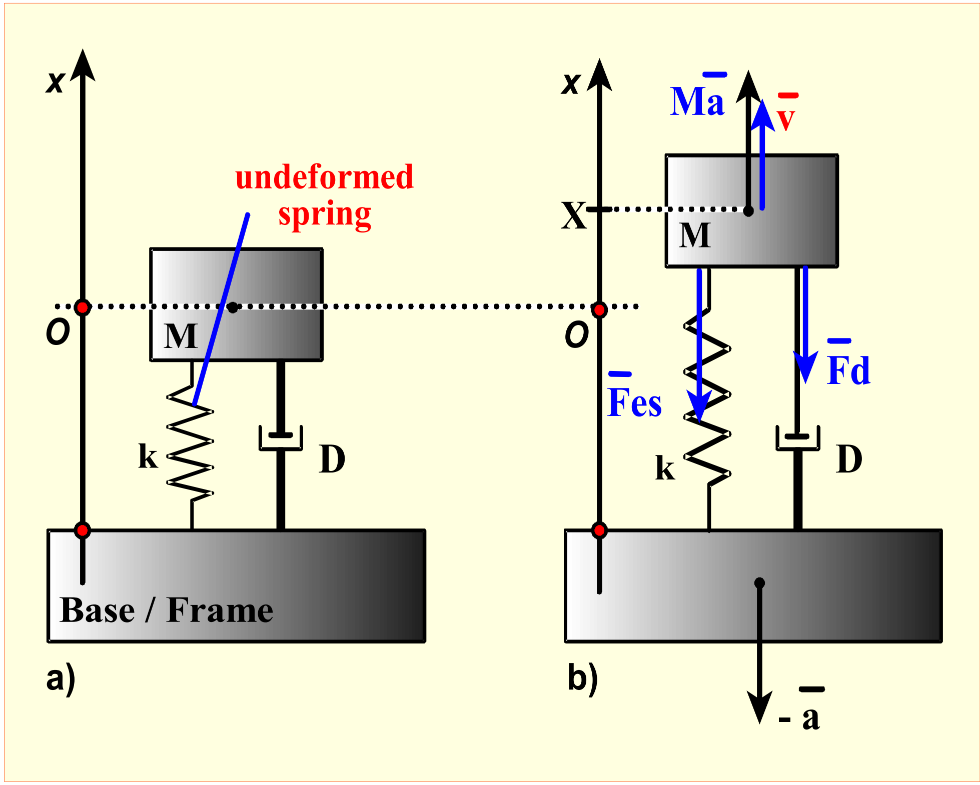
Acceleration

Input signal (inertial force)

Elastic force

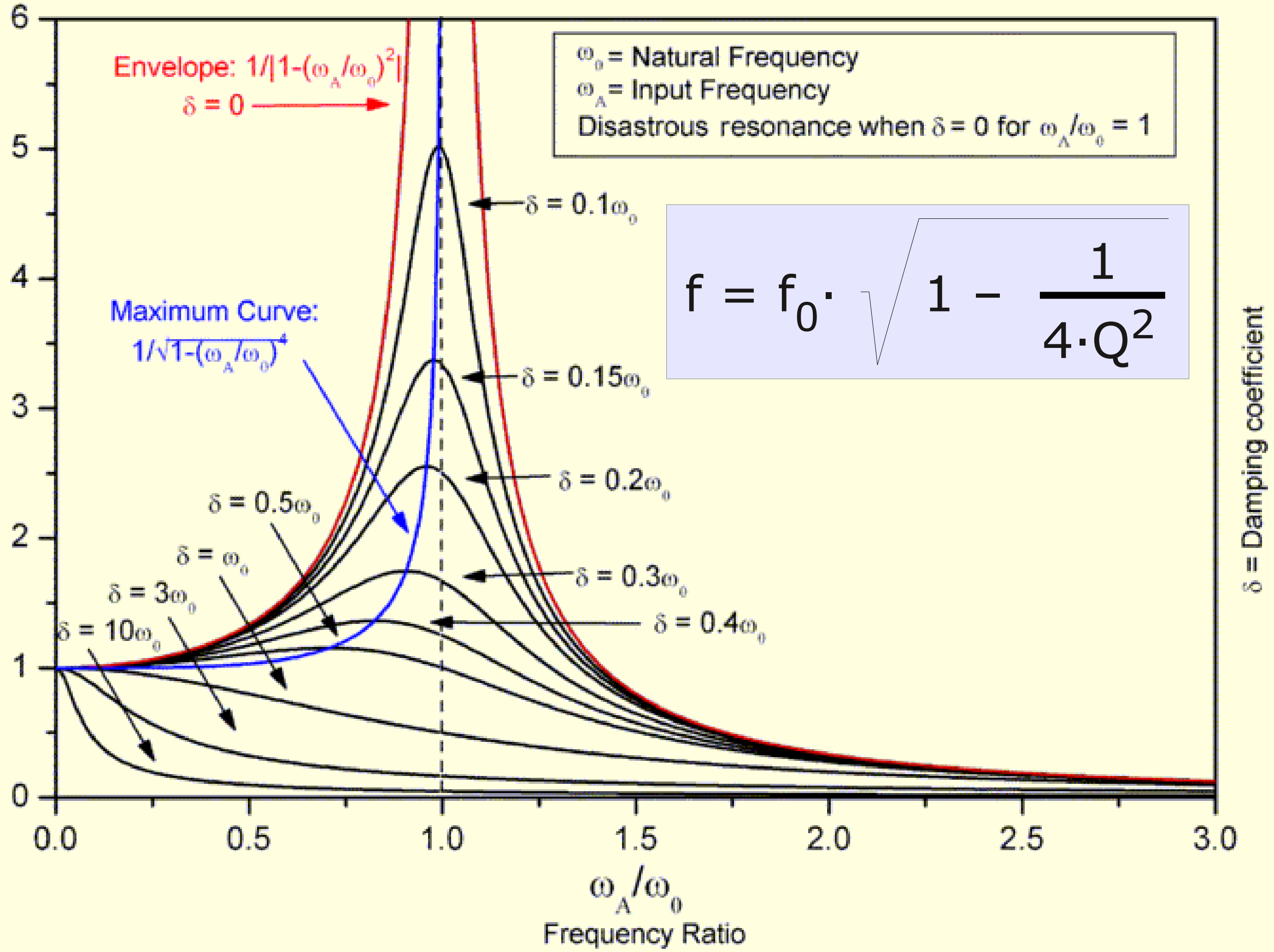
Damping force

Speed



The equation is solved for a pure sinusoidal acceleration ***a*·cos(*ωt*)**. The result for an arbitrary acceleration is obtained by superposition of such solutions.

Transfer Function



$$f = f_0 \cdot \sqrt{1 - \frac{1}{4 \cdot Q^2}}$$

Specifications for Accelerometers

- Sensitivity;
- Operation range;
- Frequency range;
- Resolution;
- Off-axis sensitivity;
- Full-scale non-linearity (FSN);
- Shock survival;
- Offset;
- Drift.

PARAMETER	AUTOMOTIVE	NAVIGATION
Operation Range	±50 g (airbag) ±2 g (vehicle stability system)	±1 g
Frequency Range	DC to 400 Hz	DC to 100 Hz
Resolution	< 100 mg (airbag) < 10 mg (vehicle stability system)	< 4 µg
Off-Axis Sensitivity	< 5%	< 0.1%
FSN	< 2%	< 0.1%
Max. Shock	> 2000 g	> 10 g
Temperature Range	–40 to 125 °C	–40 to 80 °C
TC of Offset	–60 mg/°C	–60 µg/°C
TC of Sensitivity	900 ppm/°C	±50 ppm/°C

Accelerometers: Sensing Principles

- **Piezoresistive:**
  - Deformation ➔ Stress ➔ Resistance change.
- **Capacitive:**
  - Deformation ➔ Displacement ➔ Capacitance change.
- **Tunneling:**
  - Deformation ➔ Displacement ➔ Barrier change.
- **Resonant:**
  - Deformation ➔ Stress ➔ Resonance frequency change.
- **Optical:**
  - Deformation ➔ Phase change ➔ Interference pattern.
- **Piezoelectric:**
  - Deformation ➔ Generation of electrical charges.

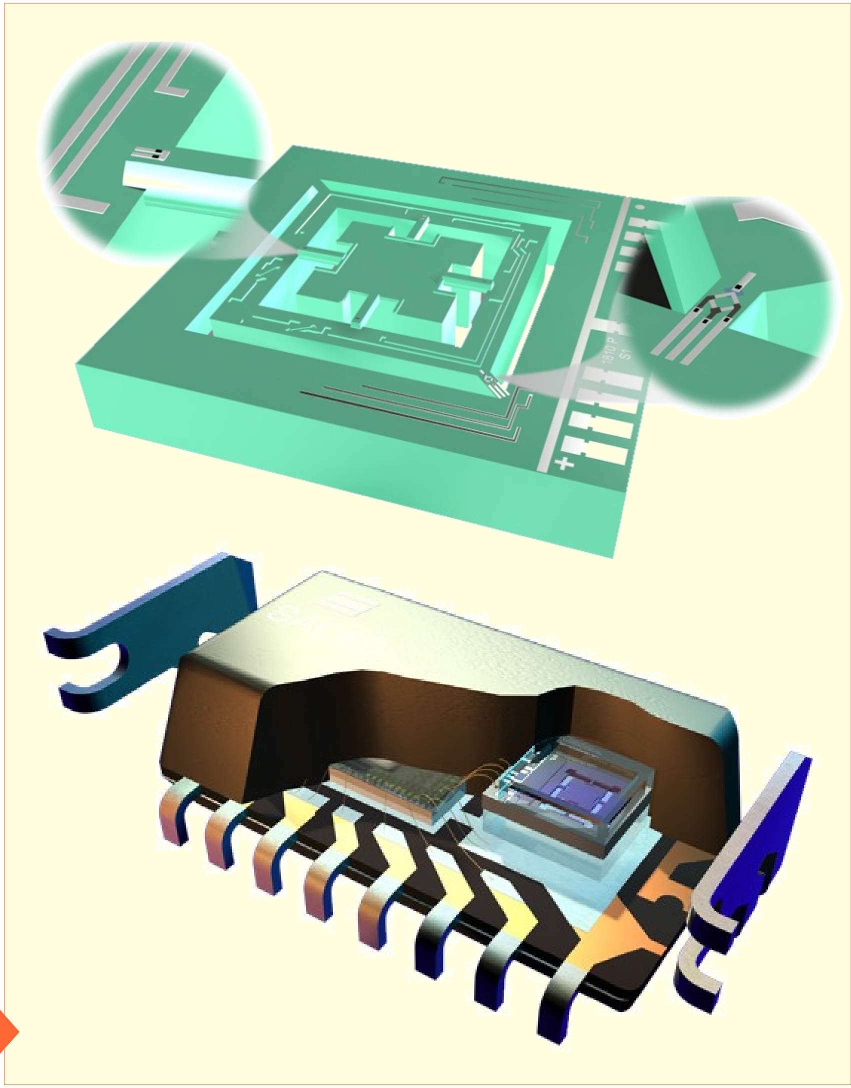
Outline

Piezoresistive Accelerometers Trade-offs

- Advantages:
  - Simpler structure;
  - Simpler fabrication process (based on bulk micromachining);
  - Simpler read-out circuitry.
- Drawbacks:
  - Larger temperature sensitivity;
  - Lower mechanical sensitivity;
  - High power consumption.

SensoNor's Crash Sensors

- Key features:
  - *Surface piezoresistors*;
  - *Self-test* features;
  - High aspect ratio front side RIE to produce free standing structures;
  - Hermetically sealed cavities with electrical feed-throughs (by triple-stack *anodic bonding*).
- **SA50:**
  - 2-axes crash sensor.
- **SAC60:**
  - 1-axis side crash sensor.



SA50 (above) and SAC60 (below) crash sensors. SensoNor Technologies AS.

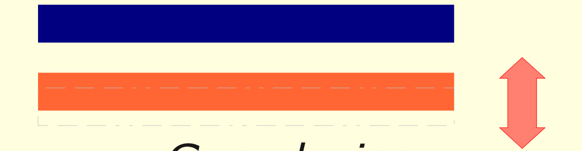
Outline

Capacitive Accelerometers Trade-offs

- Advantages:
  - High sensitivity;
  - Good DC response and noise performance;
  - Low drift;
  - Low temperature sensitivity;
  - Low power consumption.
- Drawbacks:
  - Susceptible to electromagnetic interference,
    - Shielding and suitable packaging required;
  - Nonlinear output;
  - Somewhat more difficult process.

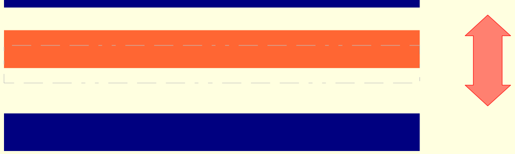
Capacitive Position Measurement

Parallel Plates



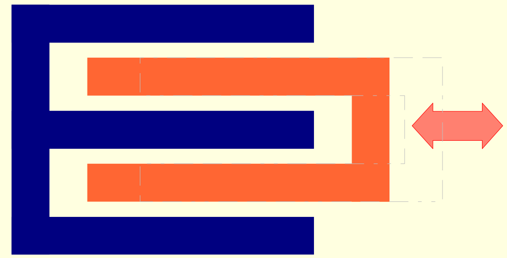
Gap-closing

Gap-overlap

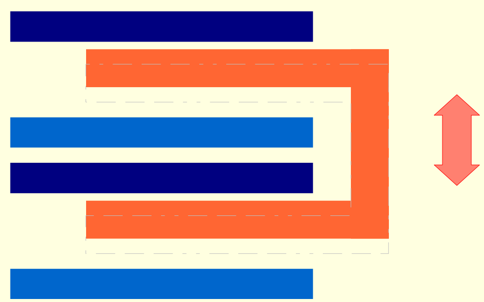


Differential gap-closing

Interdigital Plates

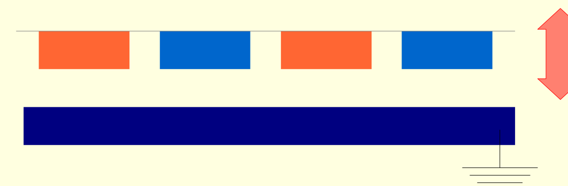


Gap-overlap



Differential gap-closing

Fringing Fields



Gap-closing

Differential gap-overlap

Differential capacitors: two capacitors that are nominally of equal size when the moveable component is centered. Achieve linearization about the balance point.

Micromachined Capacitive Accelerometers

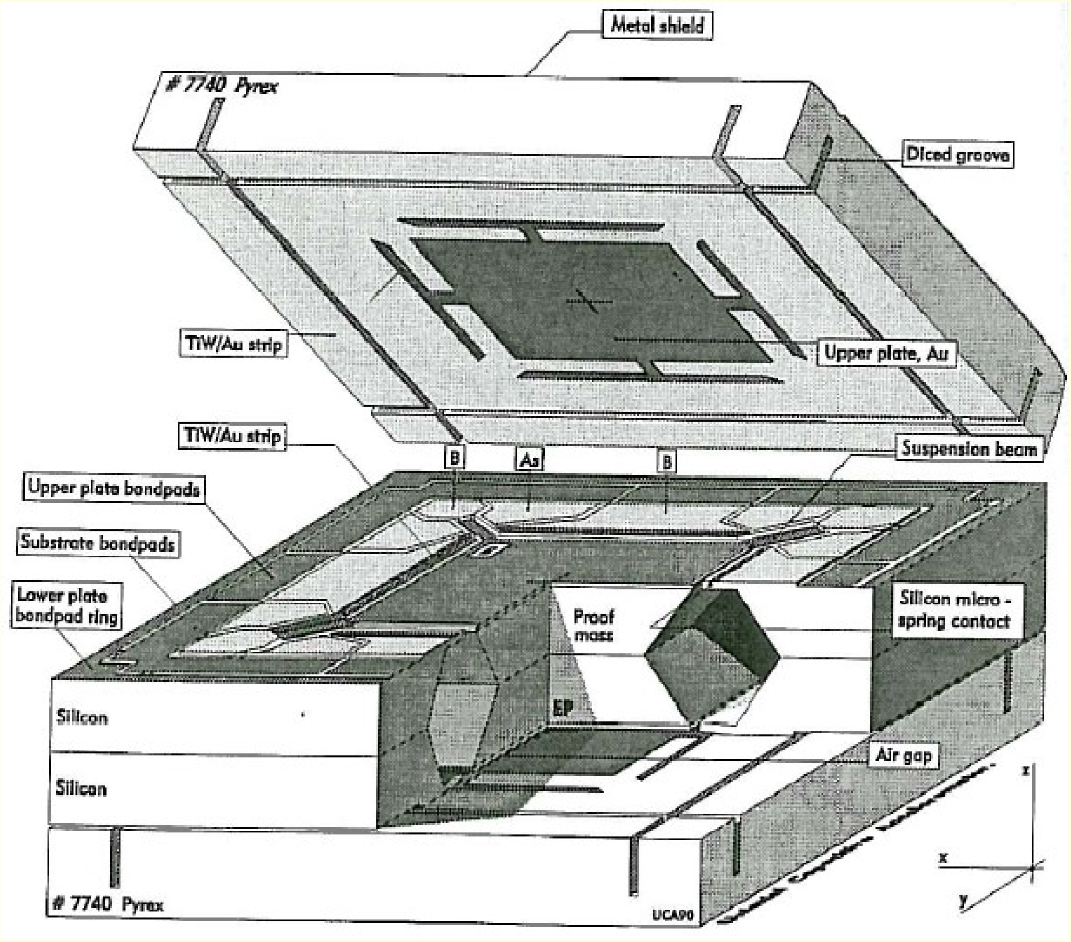
- **Bulk micromachining:**
  - Large proof mass
    ➔ *high resolution*
    (in the μg/√Hz range).
  - Requires *wafer bonding*
    ➔ larger temperature coefficients, unless made only of silicon.
  - Forming damping holes in their structural layers is not easy.
  - Requires packaging at specified pressure to control damping.

- **Surface micromachining:**
  - Utilizes deposited polysilicon layers to form the sense element.
  - Small proof mass
    ➔ *high mechanical noise*,
    ➔ *lower resolution* (in the range 100 μg/√Hz range).
  - Allows *integration* of the sensor and interface circuitry on the same chip ➔ enable detection of very small capacitance changes.
  - Does not require wafer bonding.
  - Easy to control damping.

KU Leuven's Accelerometer

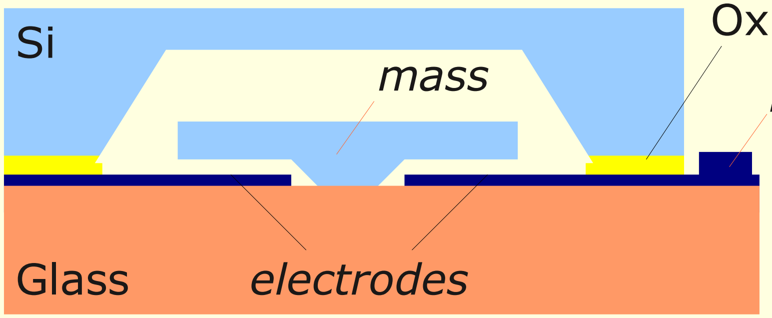
- Key features:
  - 4-wafer stack;
  - Sensor processing, including wet anisotropic etching with electro-chemical etch stop;
  - *Fusion* and *anodic bonding*;
  - *Differential*, *double-side* capacitors.

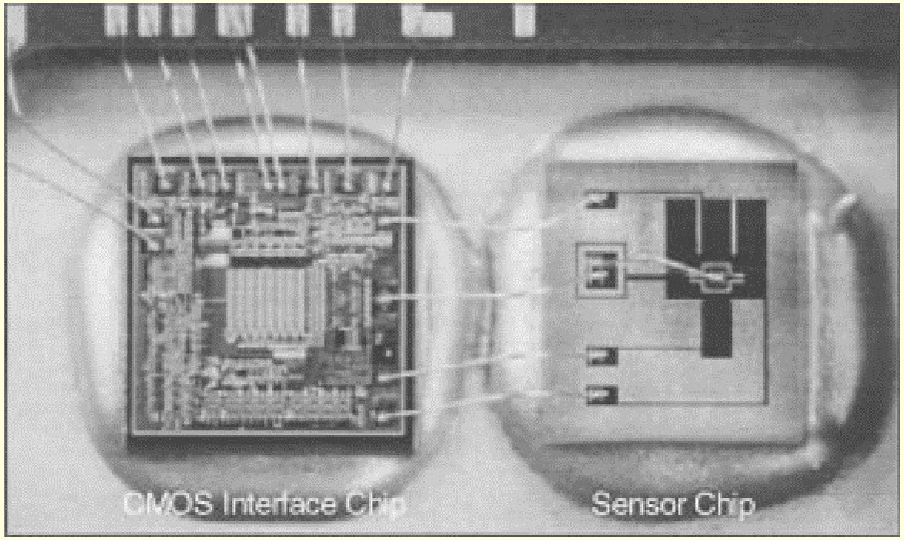
Differential accelerometer. KU Leuven.



Ford's Accelerometer

- Key features:
  - *Dissolved wafer* process;
  - Bulk micromachining;
  - Anodic bonding;
  - Used as 1-axis crash sensor.

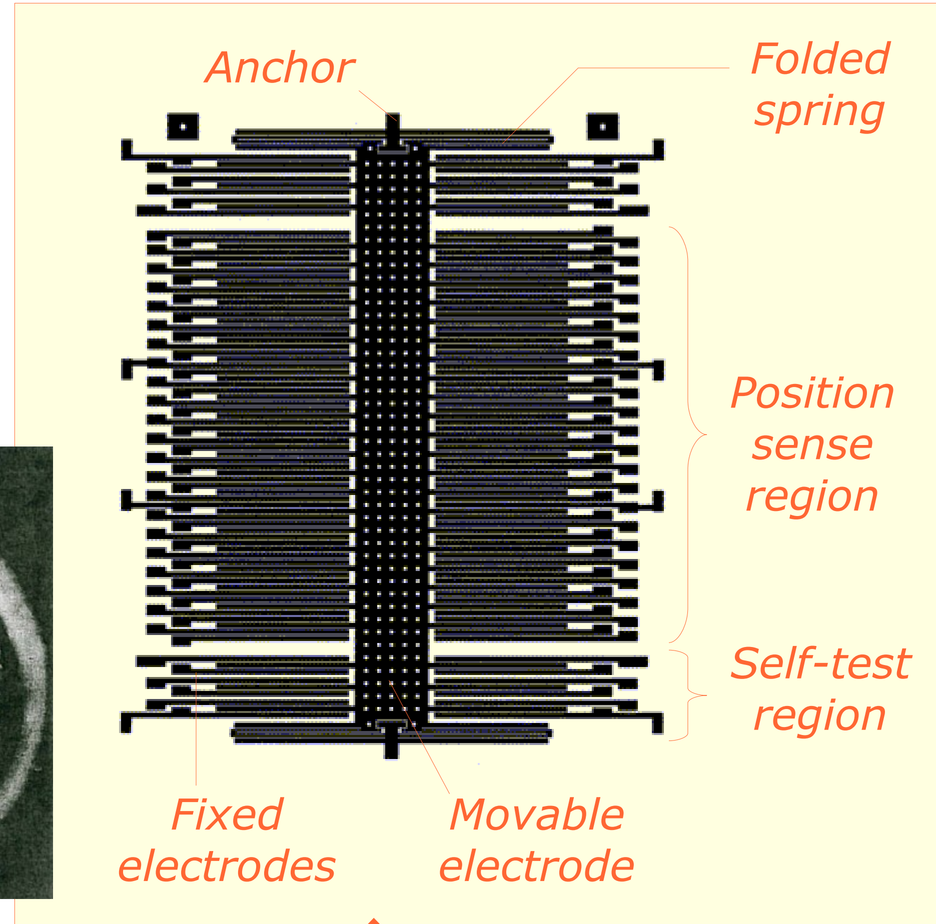


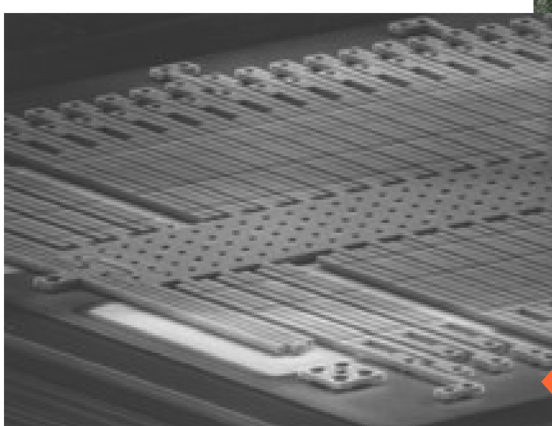


Integrated automotive accelerometer.
Ford Microelectronics, Inc.

Analog Devices' ADXL150

- Key features:
  - *Fully integrated*;
  - *Self-test* features;
  - Surface micromachining;
  - Surface mount package.





ADXL150 dual-axis accelerometer.
Analog Devices, Inc.

Outline

Tunneling Sensing Principle

- Change of *current* caused by *displacement*.

$$I_t = I_B \cdot \exp(-\alpha_I \cdot d_t \cdot \sqrt{\Phi})$$

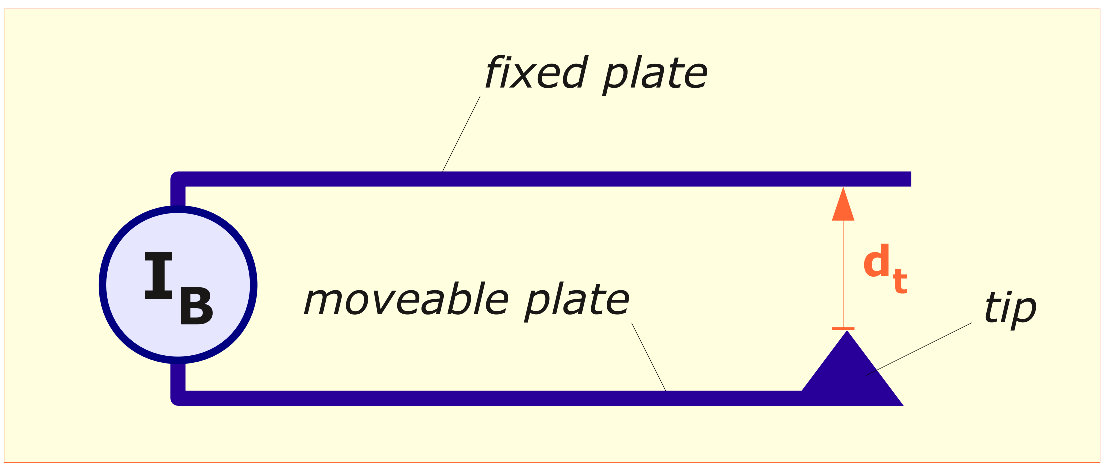
reference current

tunneling gap

tunneling barrier potential

$$\Delta I_t \sim \exp(a)$$

acceleration



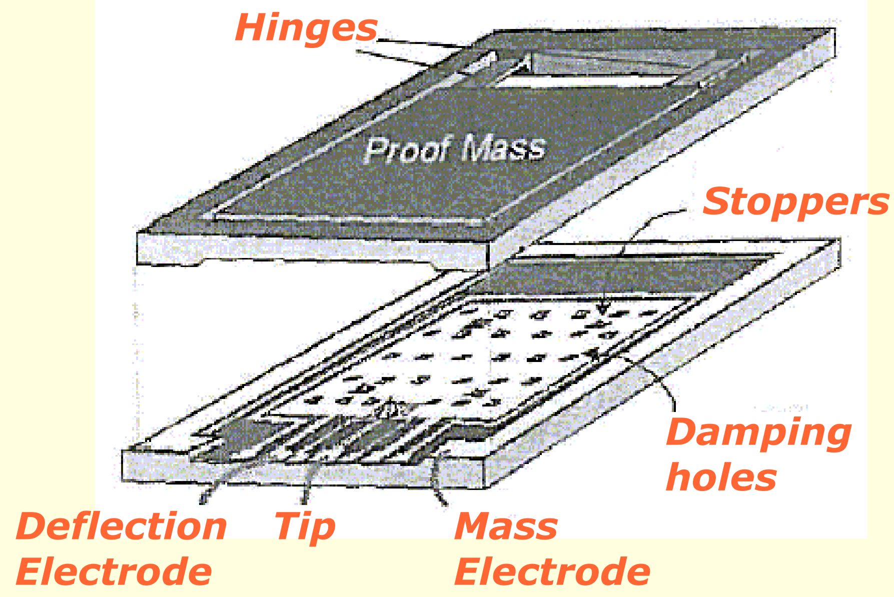
Example:
$\Delta d_t = 1\%$
➔ $\Delta I_t = 4.5\%$

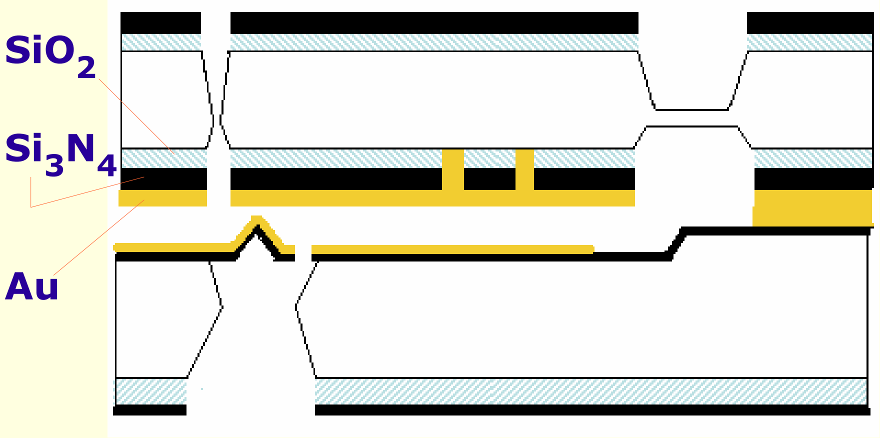
Tunneling gap d_t must be less than 10 Å.

Northwestern University's Accelerometer

- Key features:
  - Bulk micromachining,
    - can be realised in surface micromachining as well;
  - *Epoxy bonding*;
  - *Electrostatic actuation*;
  - Resolution: 10 ng.
- Principle:
  - Acceleration...
    ➔ change of tip position...
    ➔ change of tunneling current...
    ➔ change of feed-back bias.

Bulk micromachined tunneling accelerometer. Northwestern University.





Outline

1. Classification of Sensors

2. Applications

3. MEMS Technologies

4. Pressure Sensors

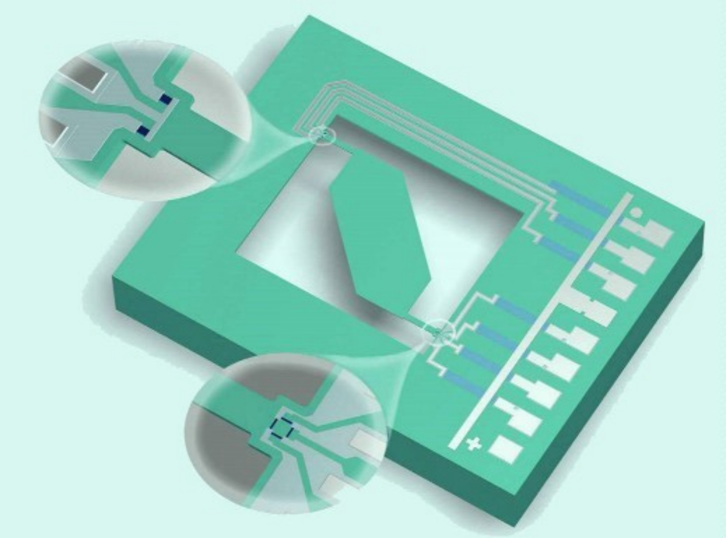
5. Accelerometers

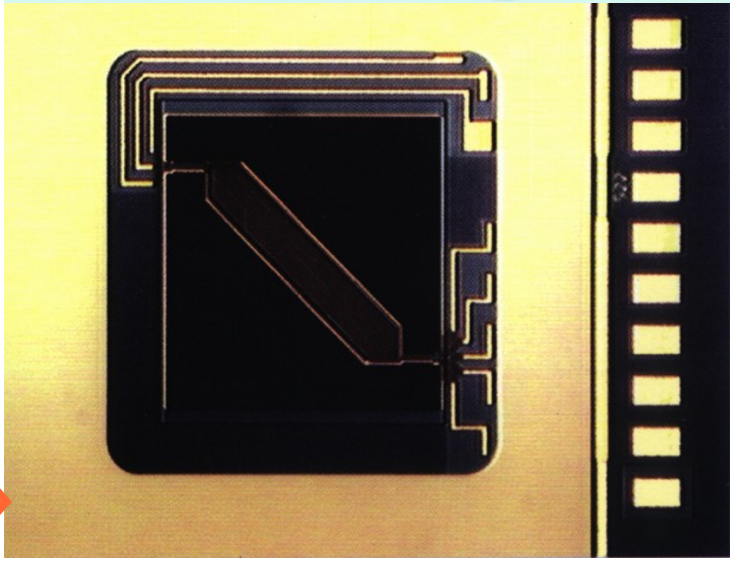
5.4. Resonant Accelerometers

6. Gyroscopes

SensoNor's Force Sensor

- **SA30** key features:
  - Resonant sensor with *thermal excitation*;
  - *Piezoresistive detection* with high sensitivity surface piezoresistors;
  - High precision spring and mass definition (by anisotropic wet etching, electrochemical etch-stop and RIE);
  - Hermetically sealed cavities with electrical feed-through (by triple-stack *anodic bonding*);
  - Used as 1-axis crash sensor.





SA30 force sensor.
SensoNor Technologies.

MultiMEMS

Accelerometer
Challenges and Future Trends

- Low cost, sub-µg noise levels, long-term stability and low temperature sensitivity inertial-grade *accelerometers*.

- Low stress, low drift *packaging technologies* for inertial-grade devices.

- Low drift read-out and control *circuitry* with high sensitivity, low noise level and large dynamic range.

- Highly stable inertial-grade *multi-axis* devices with sub-µg resolution.

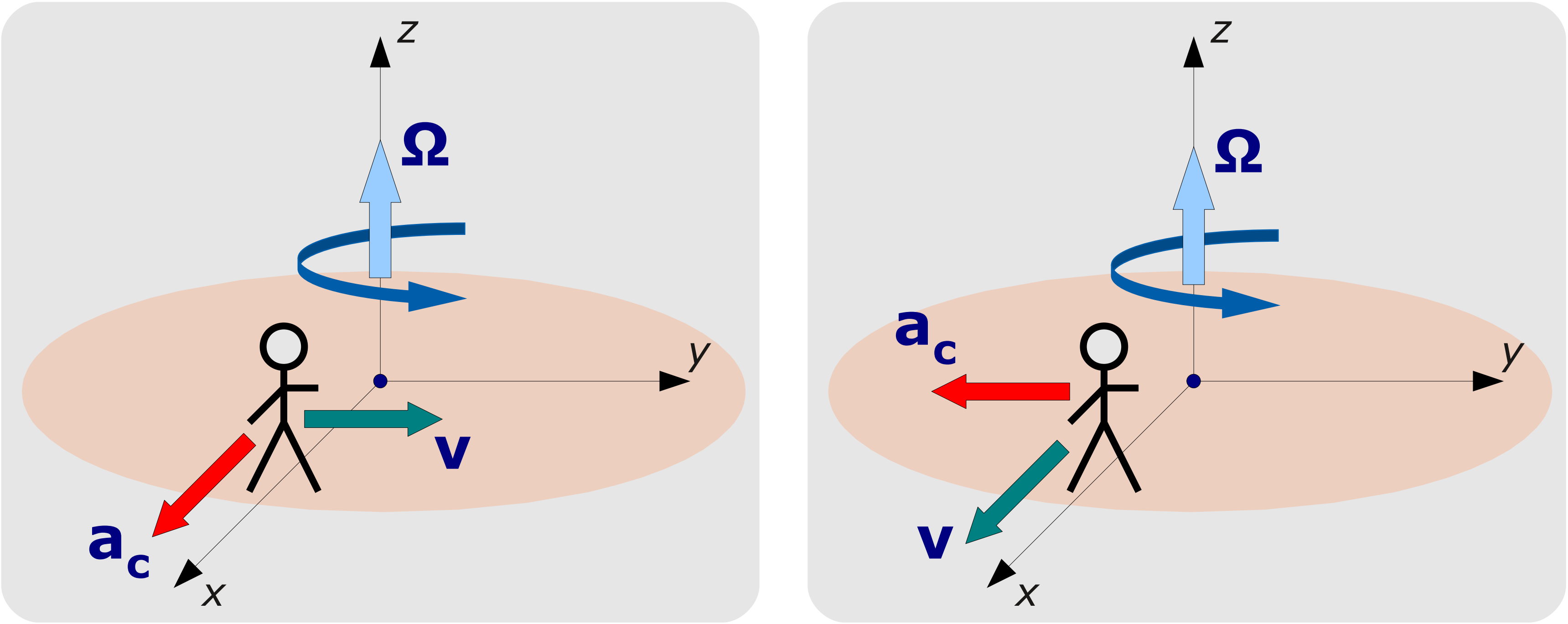
Outline

1. Classification of Sensors
2. Applications
3. MEMS Technologies
4. Pressure Sensors
5. Accelerometers
6. **Gyroscopes**

Coriolis Force

- Acts within *rotating* reference frames on masses that move with a non-zero *linear velocity*.

$$\mathbf{a_c} = 2 \cdot \mathbf{v} \times \mathbf{\Omega}$$

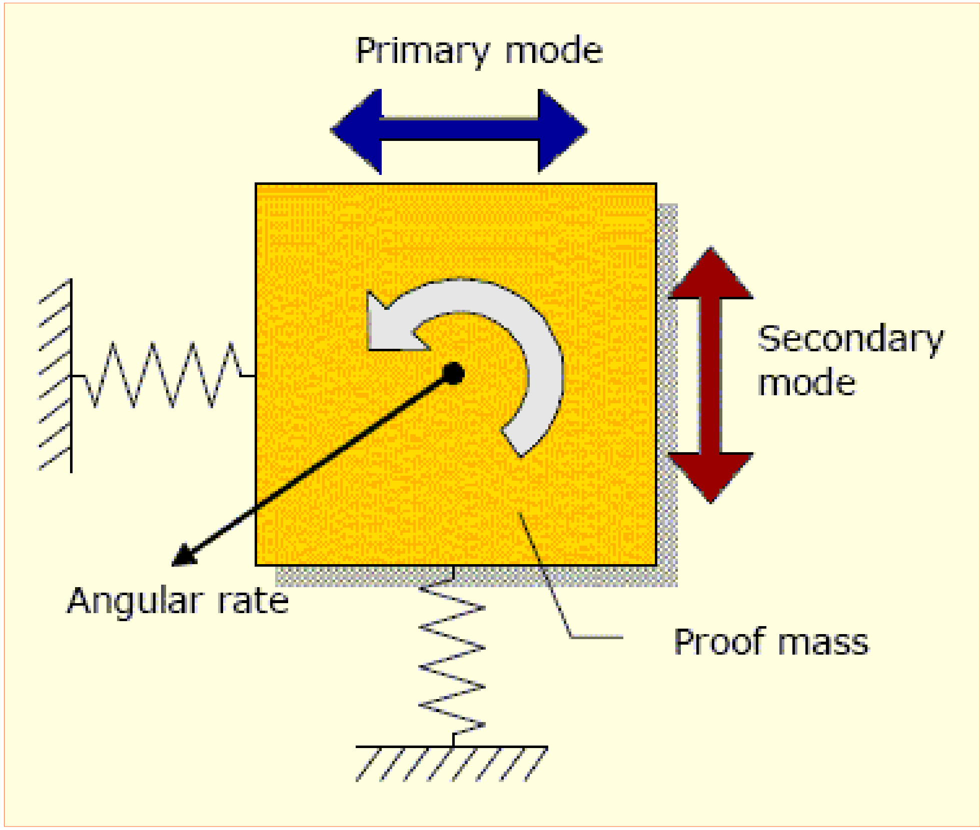


The Coriolis Rate Gyroscope

- A *resonant motion* of fixed amplitude is required in a direction perpendicular to the *axis of rotation*.

$$\mathbf{a_c} = 2 \cdot \mathbf{v} \times \mathbf{\Omega}$$

- The *Coriolis force* induces motion in the *third* direction, *perpendicular* both to the direction of rotation and to the driven motion.



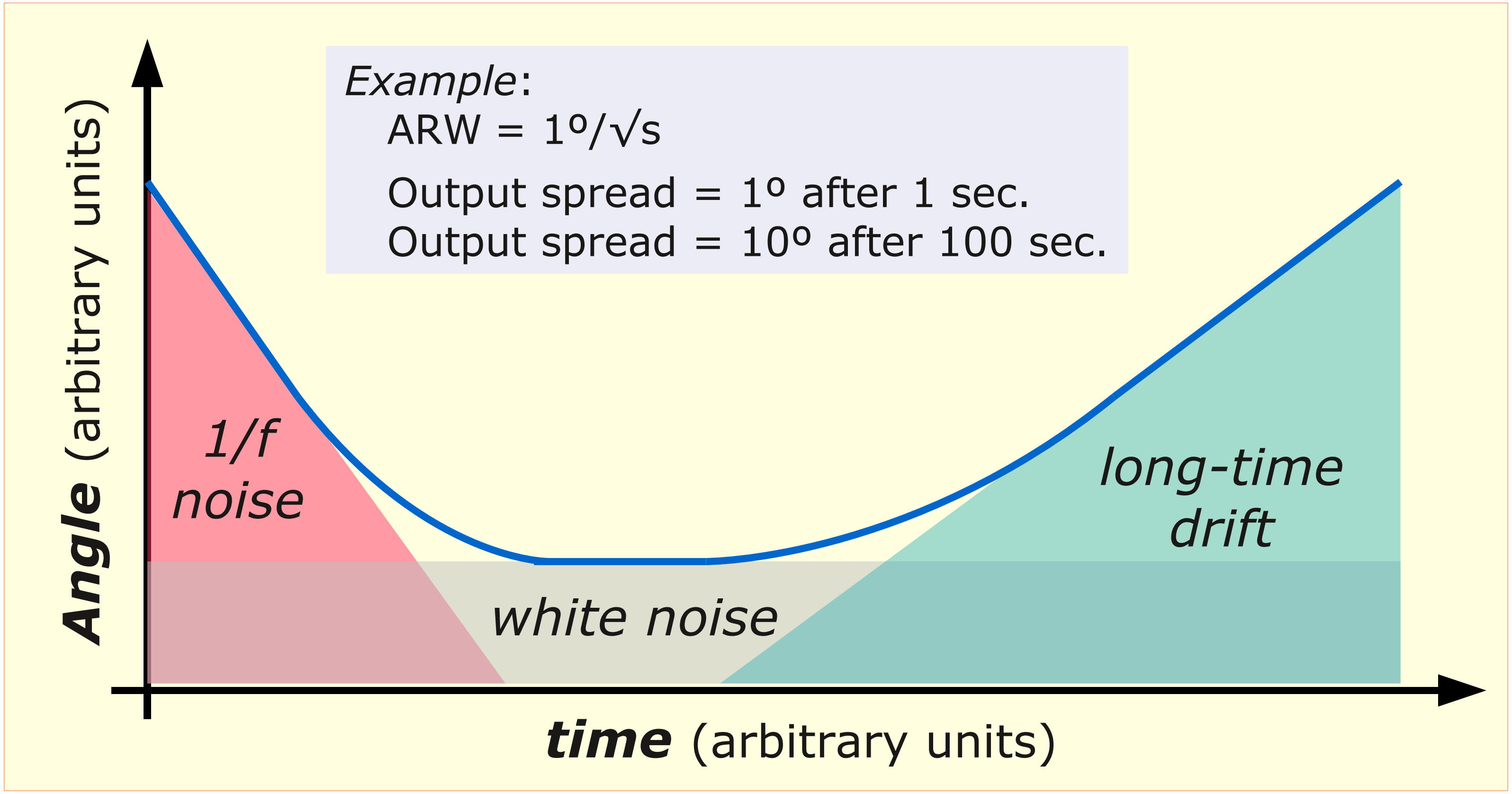
Specifications for Gyroscopes

- Sensitivity [V/(°/s)]:
  - Scale factor accuracy (SFA);
- Operation range;
- Frequency range;
- Zero-rate output;
- Output/bias drift;
- Noise,
  - Angle random walk;
- Shock survival.

PARAMETER	RATE	TACTICAL	INERTIAL
Operation Range	50... 1000 °/s	> 500 °/s	> 400 °/s
Scale Factor Accuracy	< 1%	< 0.1%	< 0.001%
Frequency Range	> 70 Hz	ca. 100 Hz	ca. 100 Hz
Output/Bias Drift	10... 1000 °/h	0.1... 10 °/h	< 0.01 °/h
Angle Random Walk	> 0.5 °/√h	0.05... 0.5 °/√h	< 0.001 °/√h
Max. Shock	1000 g	10000 g	1000 g

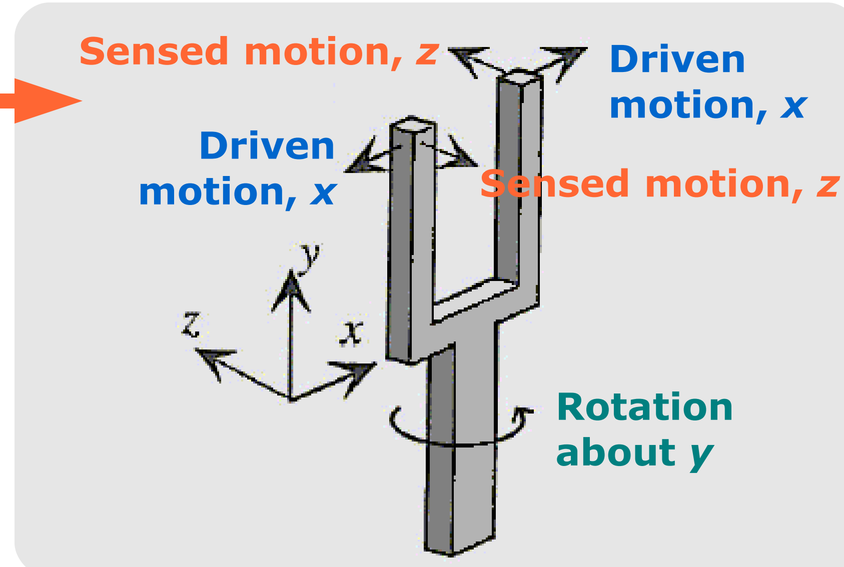
Angle Random Walk (ARW)

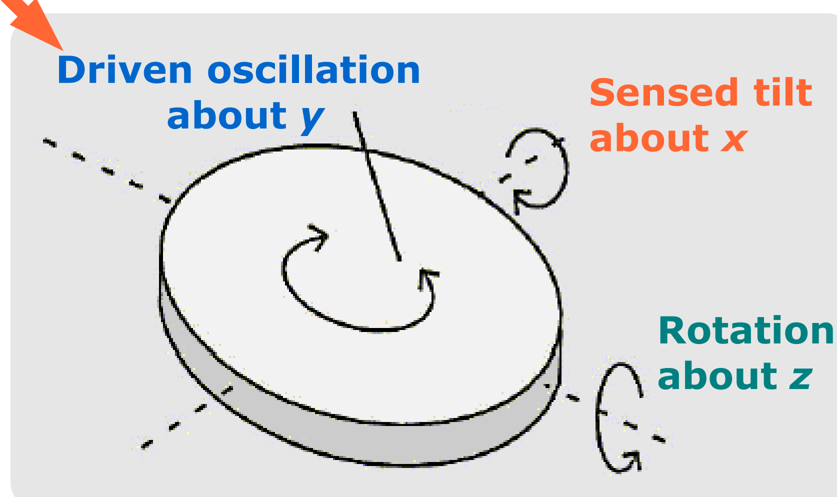
- **ARW**, a measure of gyroscope noise and stability:
  - The variation (or standard deviation) of the result of integrating the output of a stationary gyroscope over time.

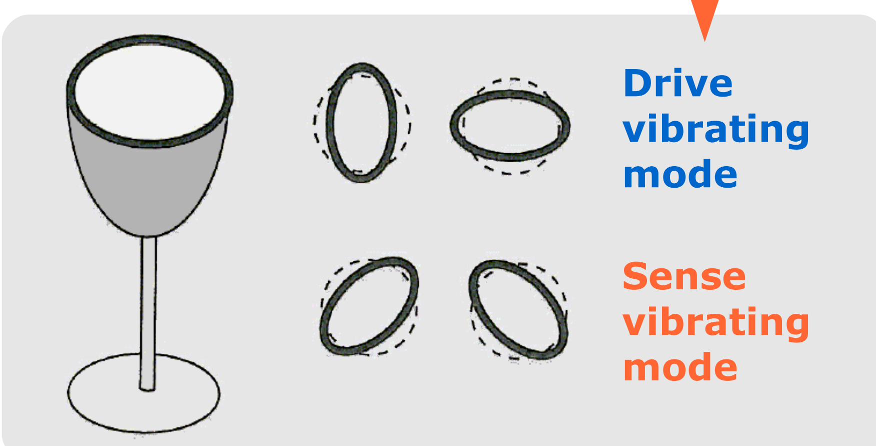


Generalized Gyroscopic Modes

- **Tuning-fork gyroscope:**
  - Driven *linear* motion.
- **Disk gyroscope:**
  - Driven *circular* motion.
- **HRG** (hemispherical resonant gyroscope)**:**
  - Driven *vibrating* mode.







Design Challenges

- A gyroscope practically consists of two high performance MEMS devices integrated in one:
  - A self-tuned *resonator* in the *drive axis* and
  - A micro-*accelerometer* in the *sensing axis*.
- Gyroscopes are very sensitive to all potential manufacturing variations, packaging, linear acceleration, temperature, etc.
- The *Coriolis force* is extremely small.
- Low-noise readout, signal processing and control *electronics* are required.
- *Packaging* issues must also be addressed in the initial phase of the design cycle.

Outline

1. Classification of Sensors

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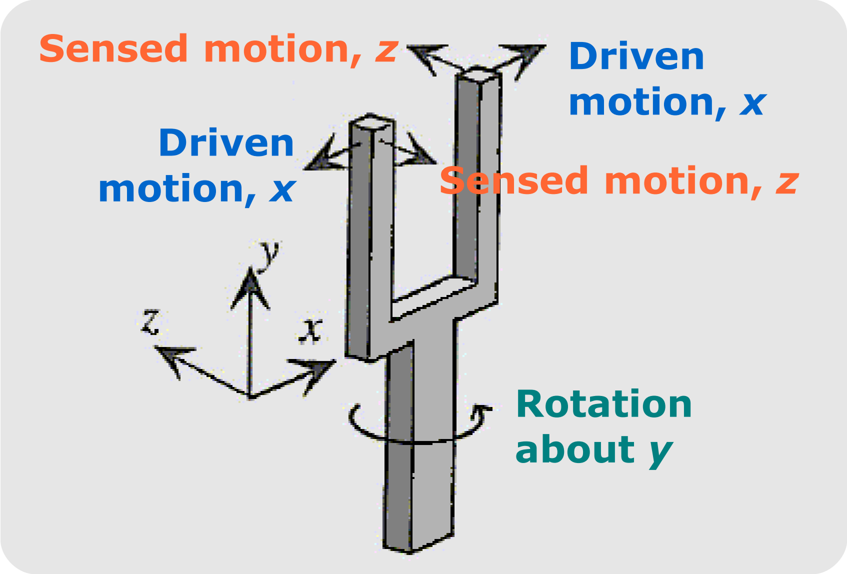
6. Gyroscopes

6.1. Tuning-Fork Gyroscopes

Operation Principle of Tuning-Fork

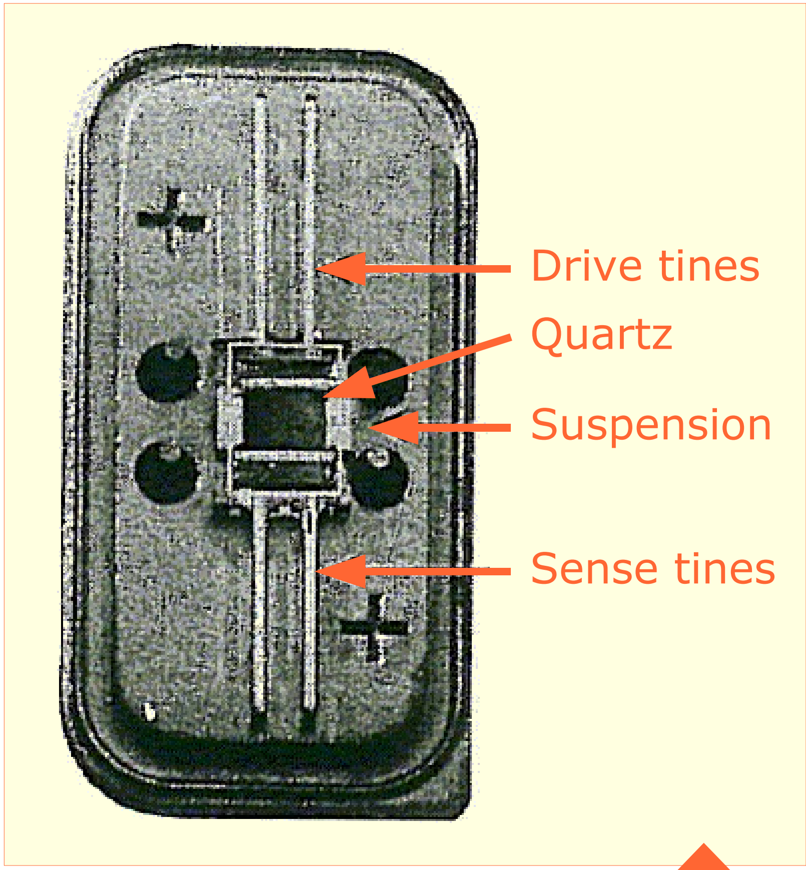
- **Excitation** (*discrete*, *linear* motion)**:**
  - Electrostatic;
  - Electromagnetic;
  - Piezoelectric.
- **Detection modes:**
  - As *differential bending* of prongs;
  - As *torsional vibration* of stem.
- **Detection principles:**
  - Capacitive;
  - Piezoresistive;
  - Piezoelectric;
  - Optical,
    - Most sensitive and most expensive.



Frequency tuning:
Maximum sensitivity is achieved when the *excitation* and *detection* resonance frequencies are equal.

Systron Donner's Gyroscope

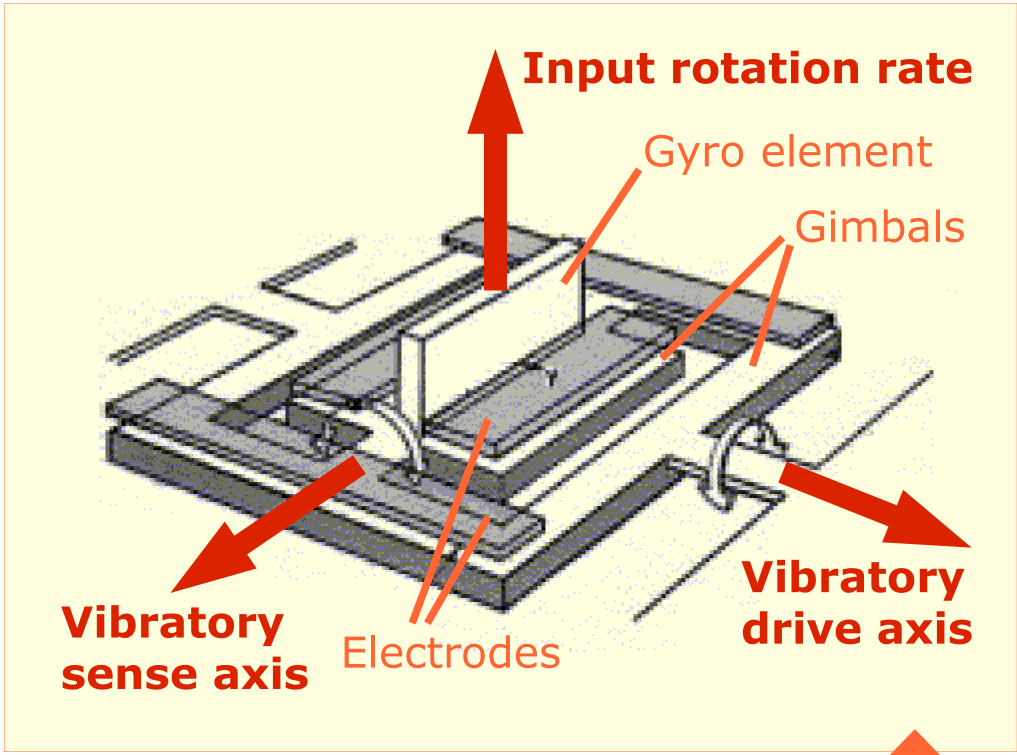
- Key features:
  - Quartz oscillator:
    - High quality factor even at atmospheric pressure,
    - High level of performance,
    - Not compatible with batch-fabrication;
  - *Piezoelectric driving*:
    - In-plane *bending* of drive tines;
  - *Capacitive sensing*:
    - Out of plane *bending* of sense tines,
    - Evaporated electrodes on sense tines;
  - Bulk micromachined;
  - Rate grade device.



Quartz gyroscope.
Systron Donner Inertial.

Draper's Double-Gimbal Gyroscope

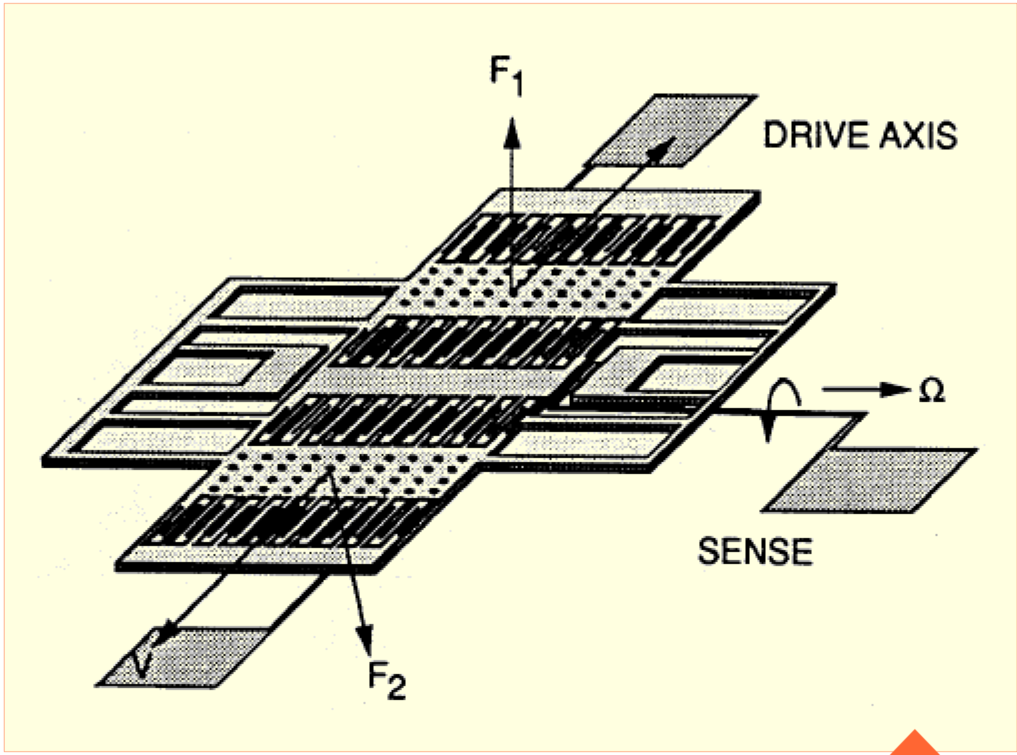
- Key features:
  - *Electrostatic driving*:
    - *Oscillation* of both gimbals;
  - *Capacitive sensing*:
    - *Oscillation* of inner gimbal;
  - Bulk micromachined;
  - *Dissolved wafer* process (silicon on glass);
  - Rate, tactical and inertial grade devices.



Double-gimbal gyroscope.
The Charles Stark Draper Laboratory, Inc.

Draper's Comb-Drive Gyroscope

- Key features:
  - *Electrostatic* comb-*driving*:
    - In-plane *antiphase vibration* of masses;
  - *Capacitive sensing*:
    - Out of plane *antiphase vibration* of masses,
    - Differential sensing,
    - Closed-loop operation;
  - Surface micromachined;
  - Perforated masses to reduce the out of plane damping;
  - *Fully integrated*;
  - Rate and inertial grade devices.

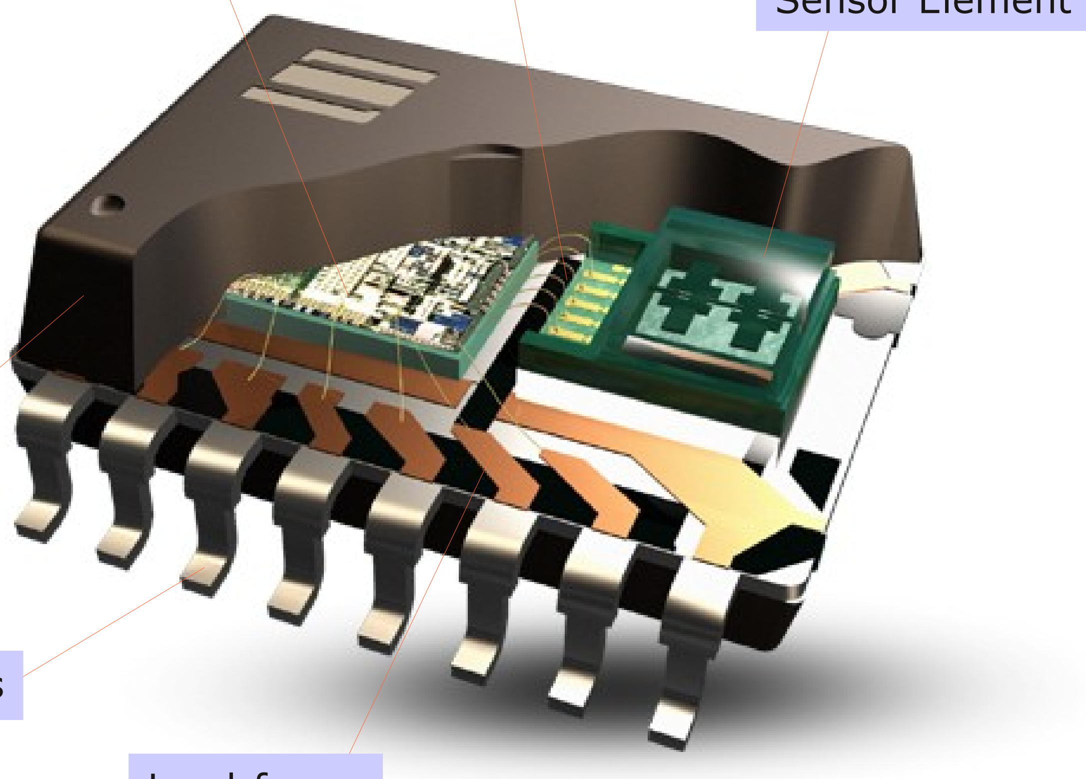


Comb-drive gyroscope.
The Charles Stark Draper Laboratory, Inc.

MultiMEMS

SensoNor's Butterfly Gyroscope

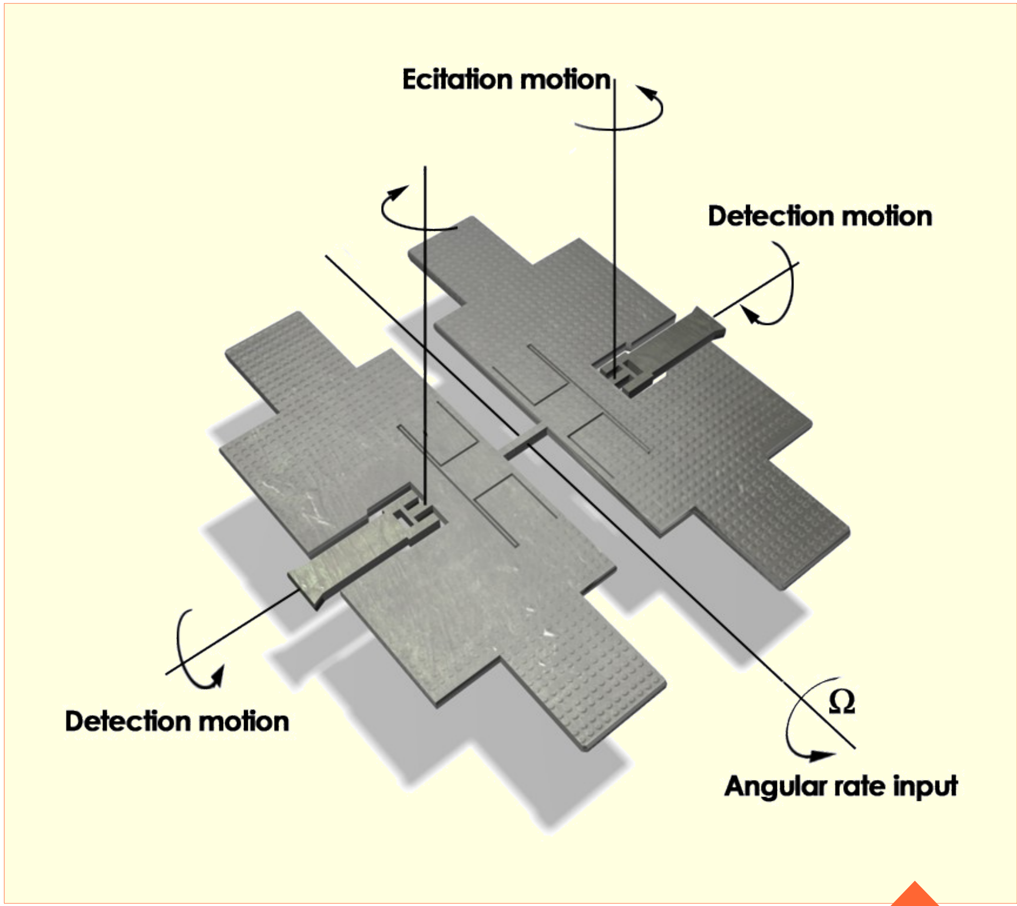
- SW510 sensor element.
- SAR10-type ASIC:
  - ADC;
  - µ-controller.
- Assembly on lead-frame in an SOIC-package.



MultiMEMS

SensoNor's Gyro Element

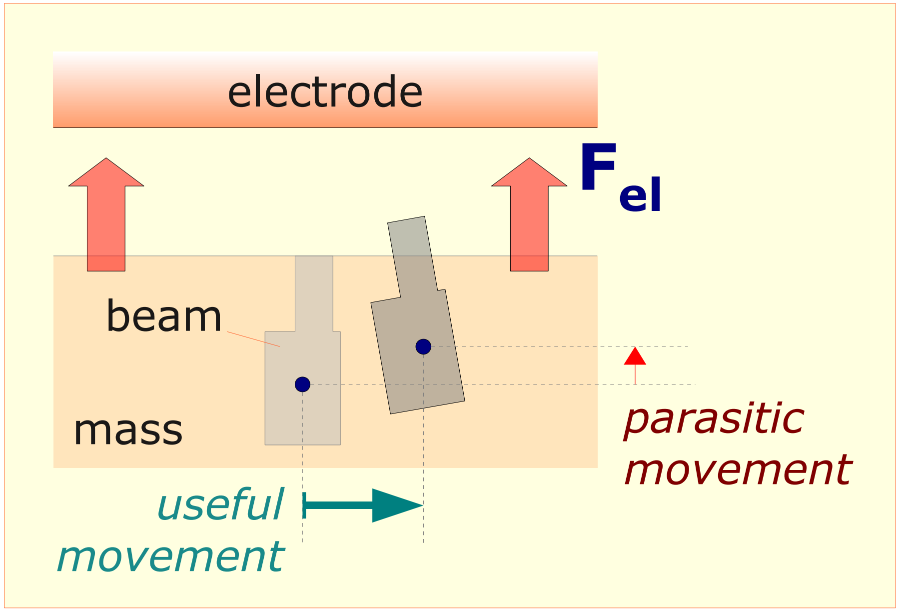
- Key features:
  - *Electrostatic driving*:
    - In-plane *antiphase vibration* of masses;
  - *Capacitive sensing*:
    - Out of plane *antiphase vibration* of masses,
    - Differential sensing,
    - Closed-loop operation;
  - Electrostatic *tuning*;
  - Bulk micromachined;
  - *Asymmetric springs*;
  - Perforated masses to reduce the out of plane damping;
  - Inertial grade device.

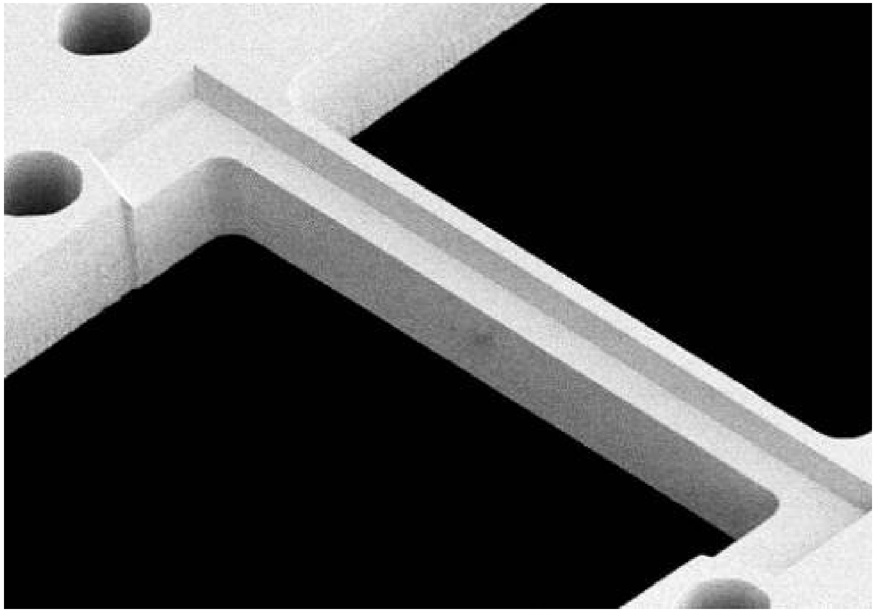


The "Butterfly" gyroscope. SensoNor Technologies AS.

Asymmetric Springs Concept

- Advantages:
  - Larger amplitude;
  - Lower Brownian noise;
  - Simpler processing.
- Drawbacks:
  - Parasitic vertical movement,
    - Excitation of parasitic mode;
  - Sensitive to tolerances;
  - Nonlinear.

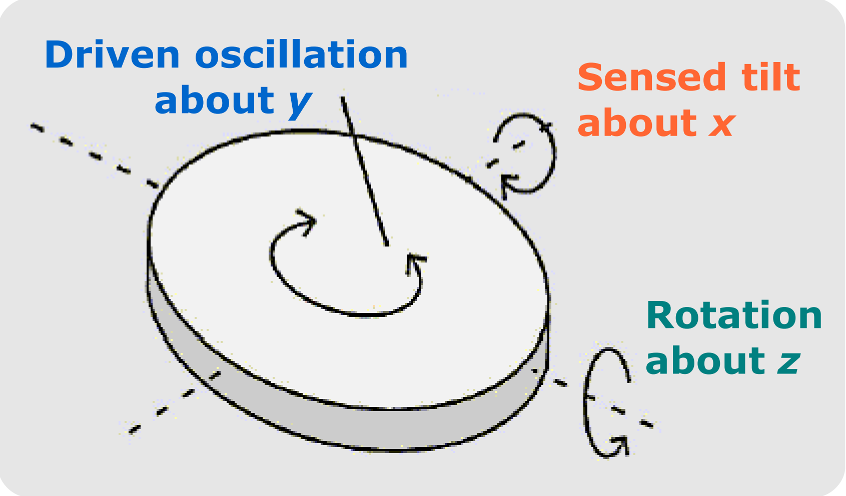




Outline

Operation Principle of Disk Gyroscopes

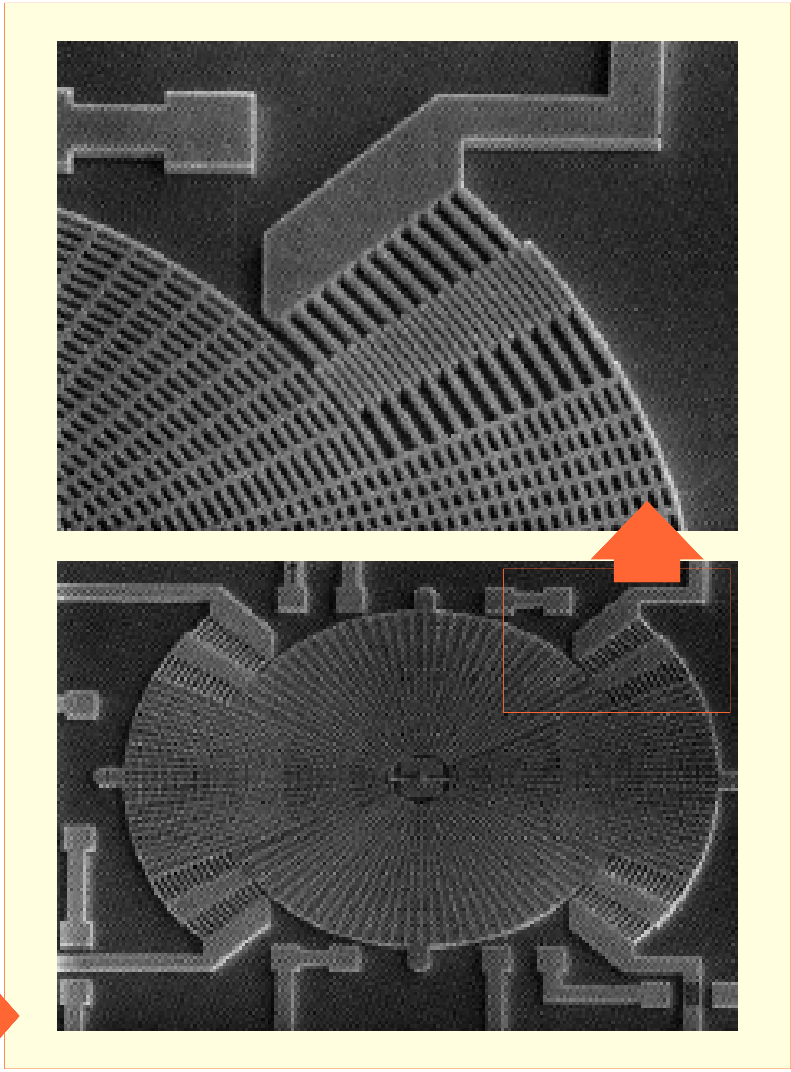
- **Excitation** (*discrete*, *circular* motion)**:**
  - Electrostatic.
- **Detection mode:**
  - As *torsional vibration* of hinges.
- **Detection principles:**
  - Capacitive,
    - Possibility to operate in closed-loop;
  - Piezoresistive;
  - Piezoelectric;
  - Optical.



Frequency tuning:
Maximum sensitivity is achieved when the *excitation* and *detection* resonance frequencies are equal.

MicroSensors' Gyroscope

- Key features:
  - *Electrostatic* comb-driving:
    - In-plane *vibration* of mass;
  - *Capacitive sensing*:
    - Out of plane *vibration* of mass,
    - Differential sensing,
    - Closed-loop operation;
  - Electrostatic *tuning*;
  - Surface micromachined;
  - Perforated disk to reduce the out of plane damping;
  - Rate grade device.



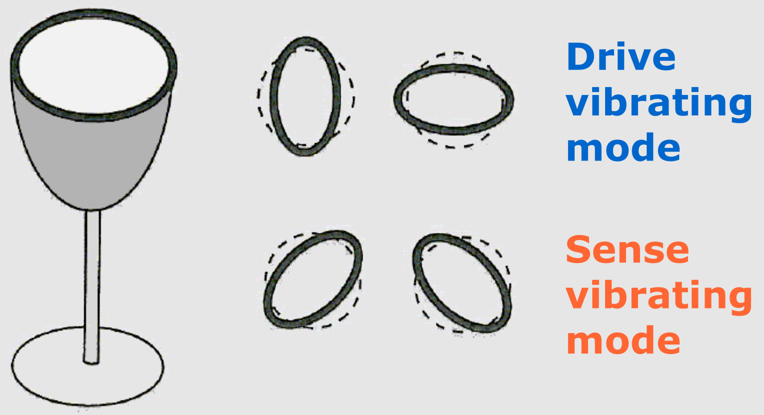
The "Silicon MicroRing Gyro". MicroSensors, Inc.

Outline

MultiMEMS

Operation Principle of HRGs

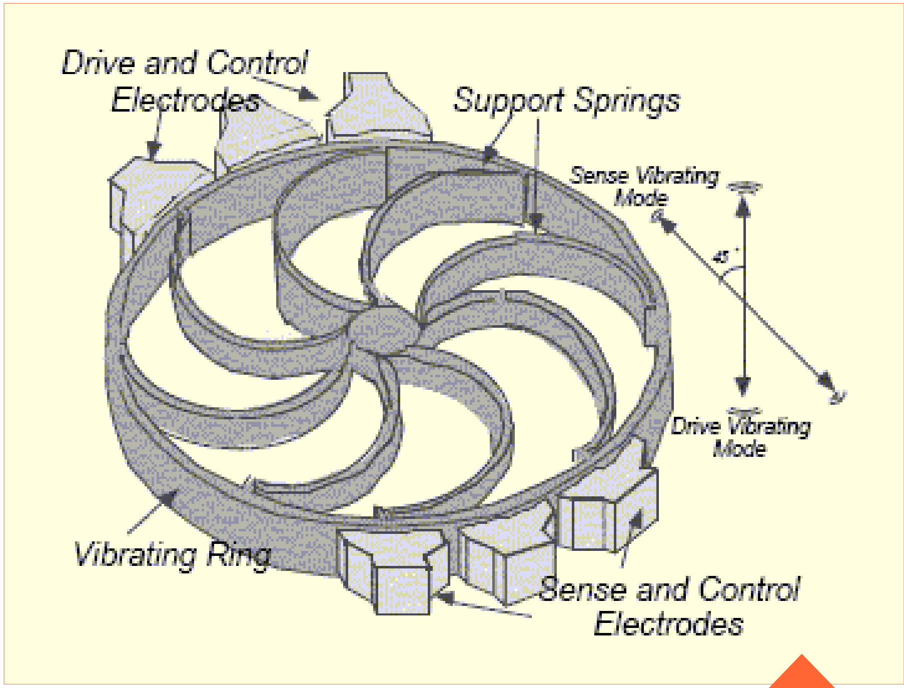
- Change of *vibration axis* of oscillators in the presence of angular rates. No temperature dependency in the first order.
- **Excitation** (*continous vibrating* mode)**:**
  - Electrostatic;
  - Piezoelectric.
- **Detection mode:**
  - As *torsional vibration* of hinge(s).
- **Detection principles:**
  - Capacitive;
  - Piezoresistive;
  - Piezoelectric.



The "Wineglass" oscillator

University of Michigan Gyroscope

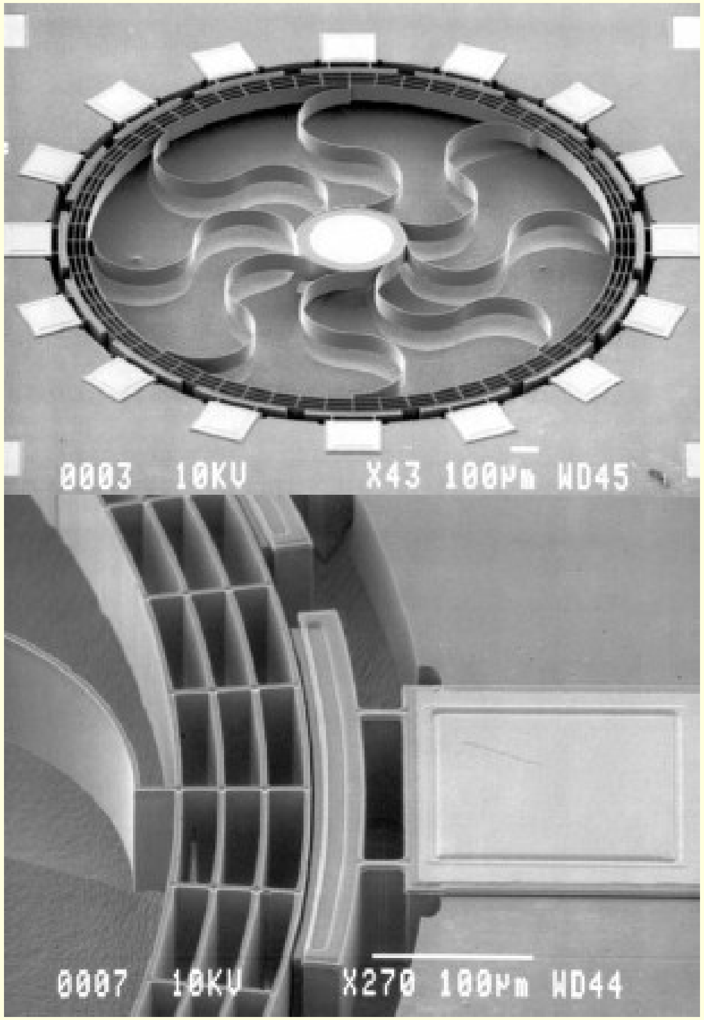
- Key features:
  - *Electrostatic driving*:
    - In-plane *vibration* of ring,
      - Elliptically-shaped primary flexural mode;
  - *Capacitive sensing*:
    - In-plane *vibration* of ring,
      - Elliptically-shaped secondary flexural mode, located 45º apart from primary mode;
  - High aspect ratio bulk and surface micromachining;
  - High degree of symmetry,
      - Low sesitivity to spurious vibrations;
  - Vibrating ring made of p^{++}/polysilicon,
      - High quality factor and sensitivity.



Vibrating ring gyroscope.
University of Michigan.

Vibrating Ring Gyroscope

- Fabricated by **HARPSS** (**H**igh **A**spect **R**atio combined **P**oly- and **S**ingle-crystal **S**ilicon) micromachining technology:
  - The ring and springs are created by re-filling deep dry etched trenches with p^{++}/polysilicon deposited over a sacrificial LPCVD oxide;
  - The electrodes are p^{++} islands hanging over an EDP-etched pit.



Vibrating ring gyroscope. University of Michigan.

Gyroscope Future Trends

- Large volume production of low-cost, high-performance, highly reliable micromachined *gyroscopes*.
- *Precision micromachining* requires mixed fabrication technologies combined with high aspect ratio deep dry etching techniques:
  - Sub-micrometer capacitor gaps through sacrificial etching;
    - Lower bias and control voltages;
  - Thick, high-aspect ratio structures with uniform material properties and high quality factor.
- Robust vacuum *packaging*:
  - Chip-level vacuum packaging.
- High-performance interface *circuitry* and dynamic electronic tuning techniques to compensate for temperature- and long-term drift.

Thank you

for your attention !