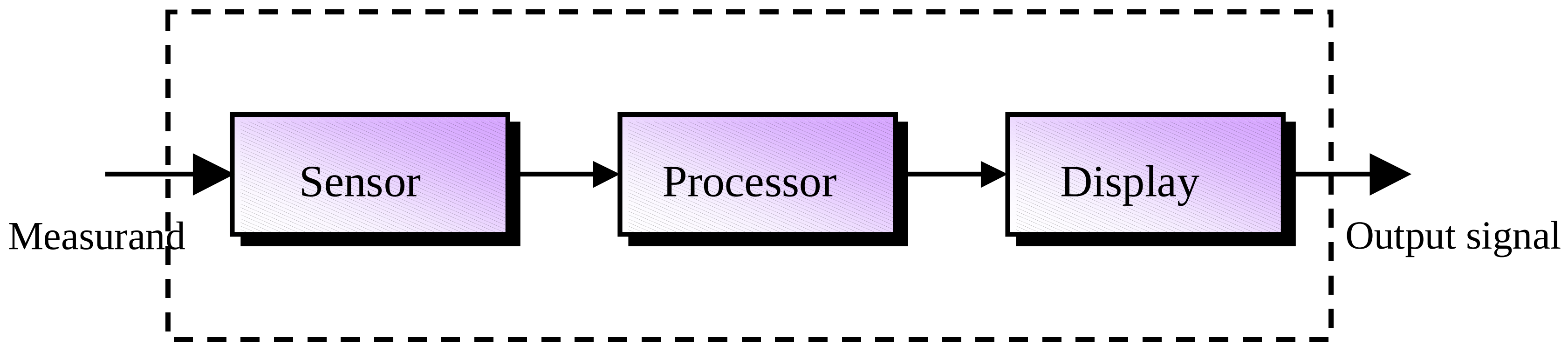
Microsensors

Outline

- Sensor & microsensor
- Force and pressure microsensors
- Position and speed microsensors
- Acceleration microsensors
- Chemical microsensors
- Biosensors
- Temperature sensors

Sensor

- Device that converts a non-electrical physical or chemical quantity into an electrical signal



Classification of sensors

Form of signal	Measurands
Thermal	Temperature, heat, heat flow, entropy, heat capacity etc.
Radiation	Gamma rays, X-rays, ultra-violet, visible and infrared light, micro-waves, radio waves etc.
Mechanical	Displacement, velocity, acceleration, force, pressure, mass flow, acoustic wavelength and amplitude etc.
Magnetic	Magnetic field, flux, magnetic moment, magnetisation, magnetic permeability etc.
Chemical	Humidity, pH level and ions, gas concentration, toxic and flammable materials, concentration of vapours and odours, pollutants etc.
Biological	Sugars, proteins, hormones, antigens etc.

- In the course book classification is based on the function that the sensor performs
  - pressure
  - position
  - acceleration
  - etc.

Sensor market

- Pressure 40 %
- Temperature 25 %
- Acceleration 13 %
- Flow 9 %
- Force 5 %

Trends in sensor technology

- Miniaturization
- Integration (sensor, signal processing and actuator)
  - sensor with signal processing circuits for linearising sensor output, etc.
  - sensor with built-in actuator for automatic calibration, change of sensitivity etc.
- Sensor arrays
  - one-function units (to improve reliability)
  - multiple-function units

Microsensors

- 1995 global sensor market 6 billion $US, 25 % from MEMS based devices
- Annual increase in the market volume 20%
- Why microsensors
  - lower manufacturing cost (mass-production, less materials)
  - wider exploitation of IC technology (integration)
  - wider applicability to sensor arrays
  - lower weight (greater portability)

Applications

- Automotive industry
  - average electronics content of a car is today 20%
  - to increase safety (air bag control, ABS), reduce fuel consumption and pollution
- Medical applications
  - measurement of physical/chemical parameters of blood (temperature, pressure, pH)
  - integrated sensors in catheters
- Consumer electronics

Applications ...

- Environmental applications
  - determination of concentration of substances (carbon monoxide, heavy metals, etc.)
- Food industry
  - contaminants and impurities
- Process industry
- Robotics
  - distance, acceleration, force, pressure, temperature

Pressure sensors

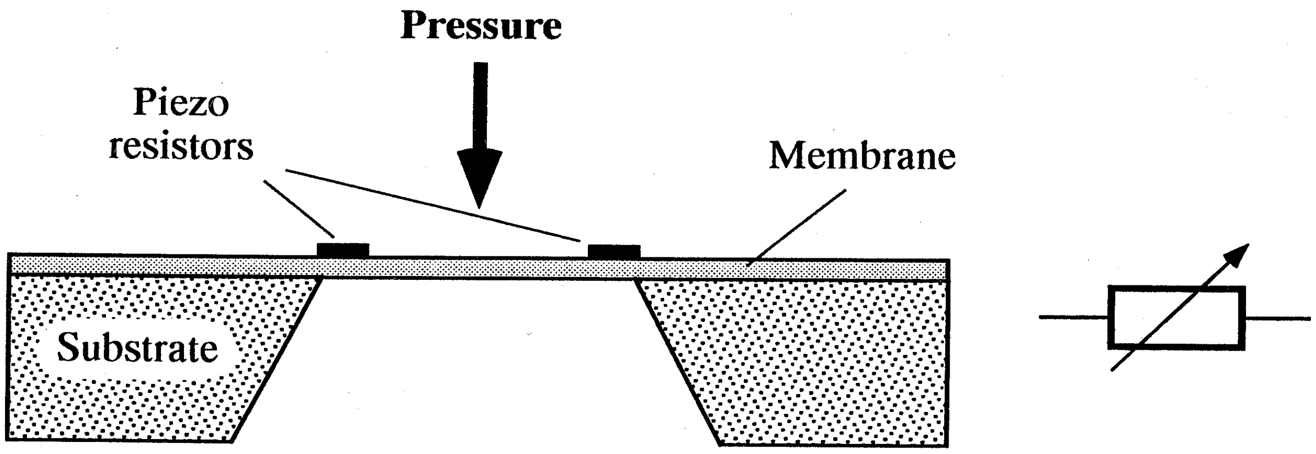
- First microsensors developed and used by industry
  - piezoresistive pressure sensor to reduce fuel consumption by a tight control of the ratio between air and fuel
  - disposable blood-pressure sensor to monitor the status of the patient during operation
- Low production costs, high sensitivity and low hysteresis
- Commercial products are usually either piezoresistive or capacitive

Pressure sensors: examples of operation principles

- Membrane sensors
  - deflection of the membrane
  - change in the resonance frequency
- Planar comb structures
- Optical methods (Mach-Zehnder interferometer)

Piezoresistive pressure sensor

- Piezoresistors integrated in the membrane
- Pressure deflects the membrane
- Resistance changes proportional to deflection and thus to pressure
- Resistance change measured with Wheatstone bridge



Capacitive membrane pressure sensor

- Membrane deflects when pressure is applied

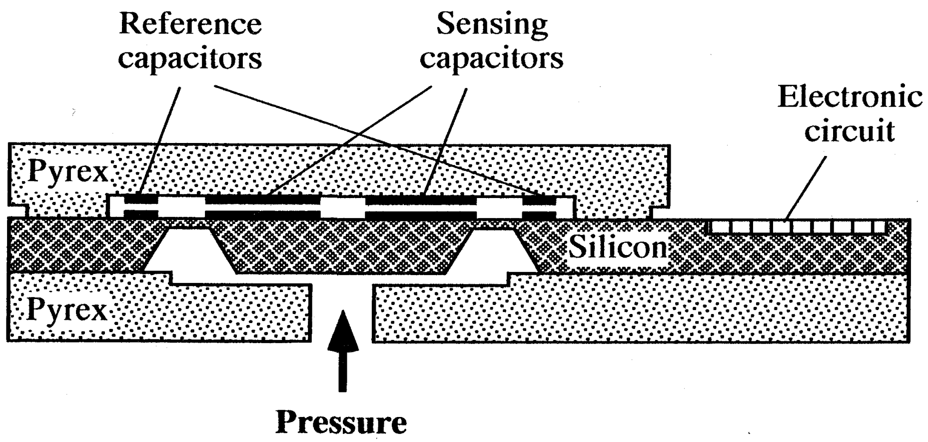
⇨ Distance between the electrodes changes

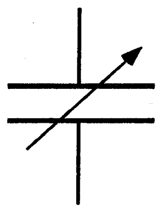
⇨ Capacitance changes

- Capacitive sensors have
  - no hysteresis
  - better long-term stability and
  - higher sensitivity but
  - higher production costs

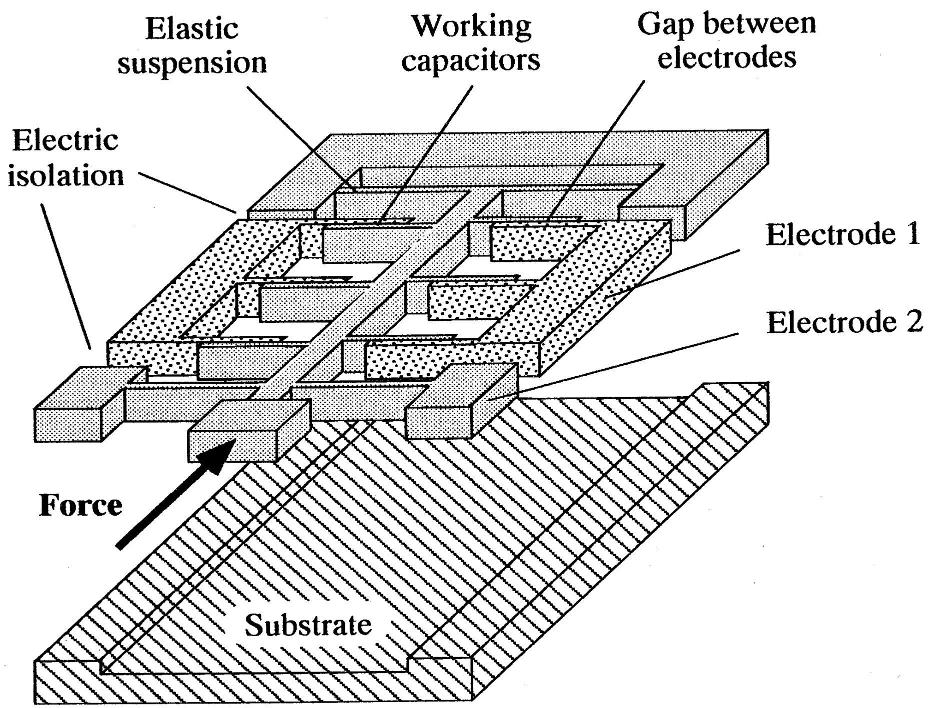
Chip dimensions: 8.4 mm x 6.2 mm

Fabrication: anisotropic etching





Capacitive pressure sensor, based on comb structure

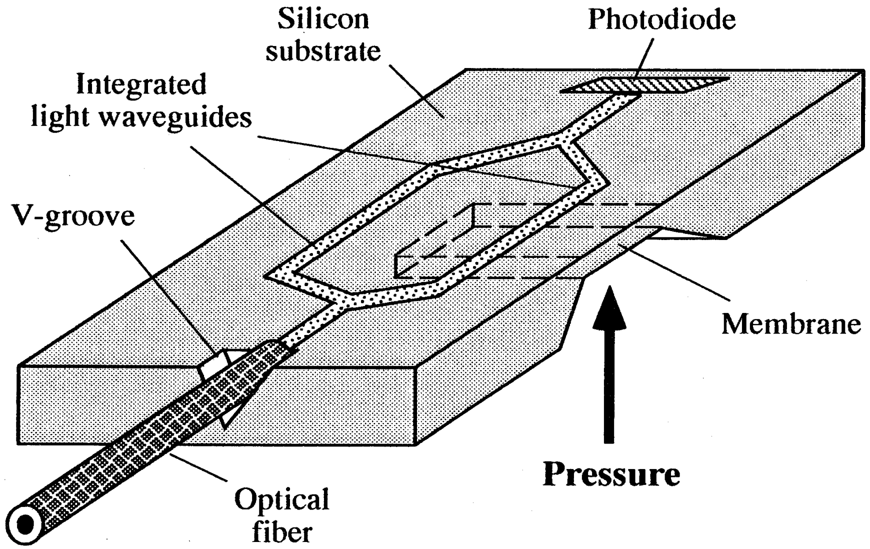


$$V_O = V_I \frac{C_1 - C_2}{C_1 + C_2}$$

Fabrication: anisotropic etching

- Utilizes parallel comb structure
- Force is applied parallel to the sensor surface
- Force is transformed into displacement => change in capacitance
- On one side capacitance increases and on the other side decreases => higher linearity and sensitivity

Mach-Zehnder interferometer



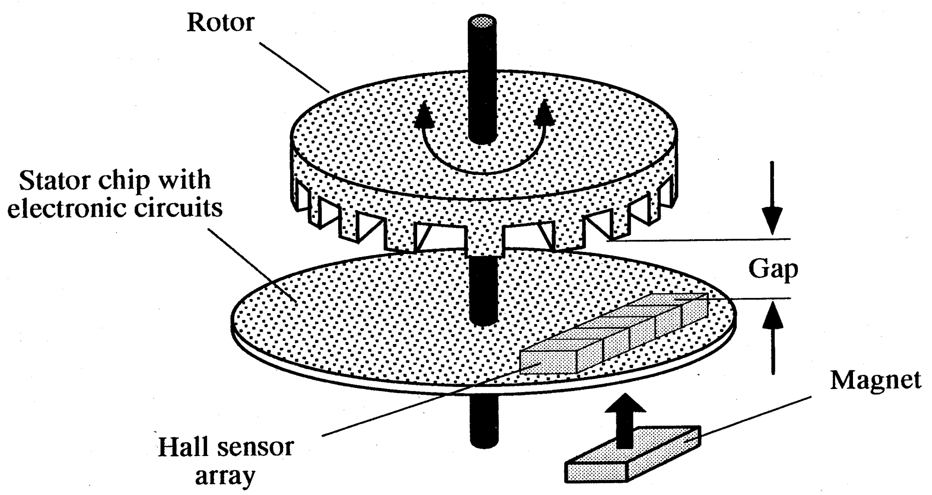
Chip size: 0.3 mm x 5 mm
Output: 14 µV/mbar

- Laser light brought into the sensor by optical fiber
- Light is split to two beams
- One light beam crosses a micromembrane which is deformed by pressure
- The deformation changes light properties
- The beams are combined and brought a photodiode
- Different propagation speeds result in phase shift

Position and speed microsensors

- Applications
  - Automobiles
  - Robots
  - Medical instruments
- Contact-free optical and magnetic methods are the most significant for MST

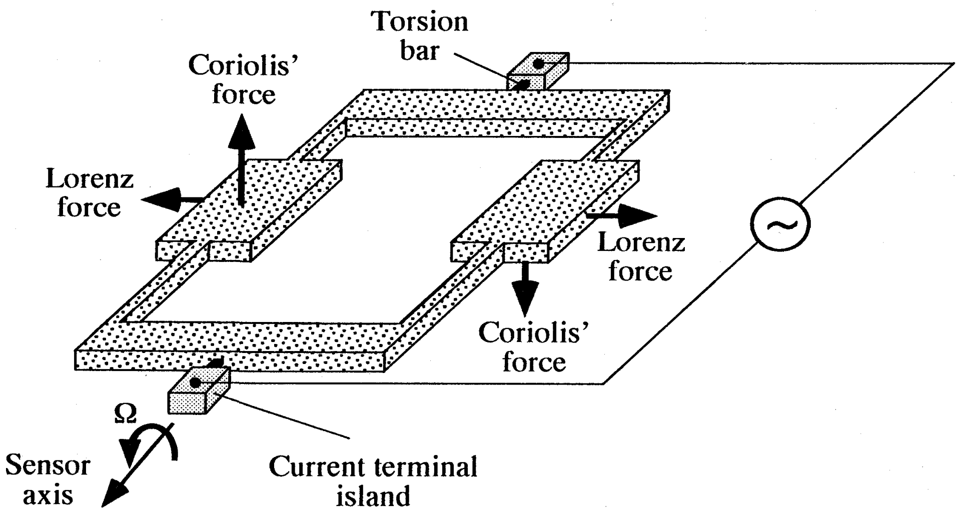
Magnetic sensor to measure angular displacement



Length: 4 mm
Resolution: 0.028 degrees

- Measurement of joint angle in robotics
- Hall sensor based measurement of angular displacement
  - Rotor with a row of teeth
  - Stator contains Hall sensors
  - Permanent magnet located under the sensors
  - Teeth passing by a Hall sensor change magnetic field

Capacitive angular speed sensor



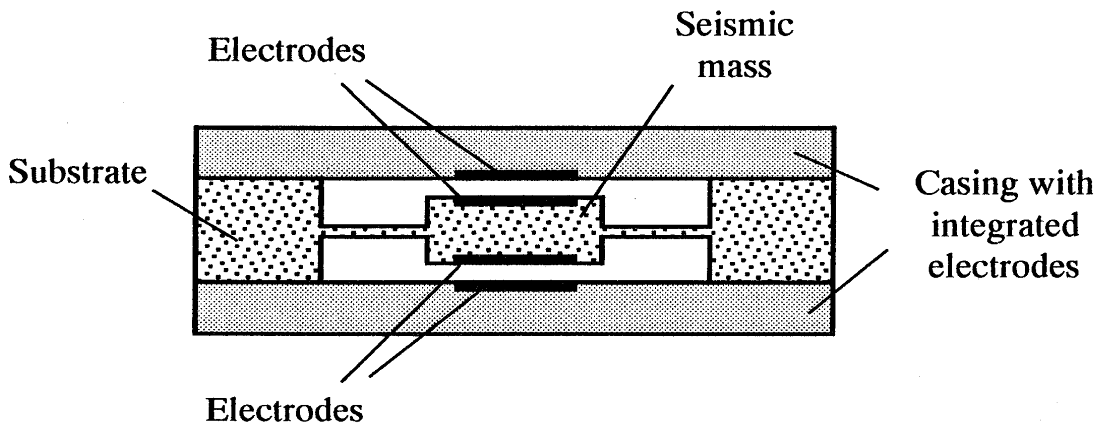
Size: 20 mm x 20 mm
Sensitivity: 0.5 mV s/deg

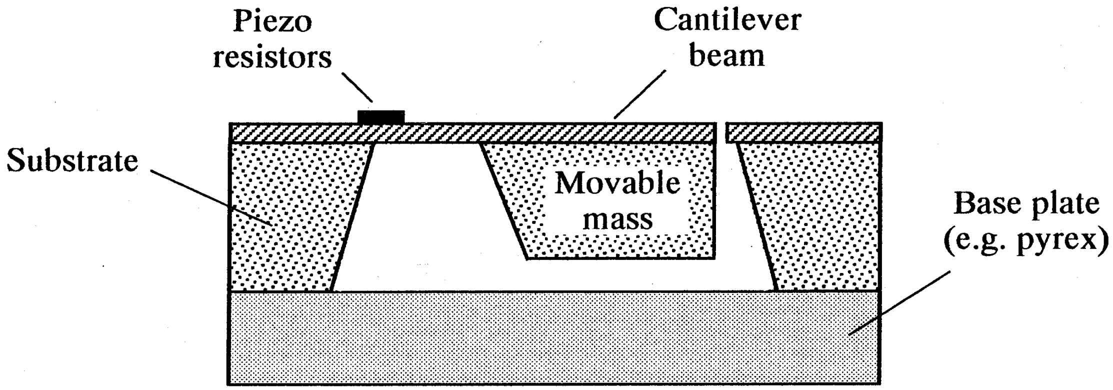
- The fork arrangement is used as a resonator
- The resonator starts to oscillate when magnetic field and alternating current are applied (Lorentz force)
- The amplitude of the swing angle is detected by the capacitance change between movable and fixed electrodes

Acceleration microsensors

- Have mostly been used in automotive industry
- Usually detected with capacitive and piezoresistive methods
- An elastic cantilever where a mass is attached is mostly used
- Under acceleration mass displaces the cantilever
- Deflection of the cantilever is detected
- By increasing the mass sensitivity can be increased

Examples of piezoresistive and capacitive principles

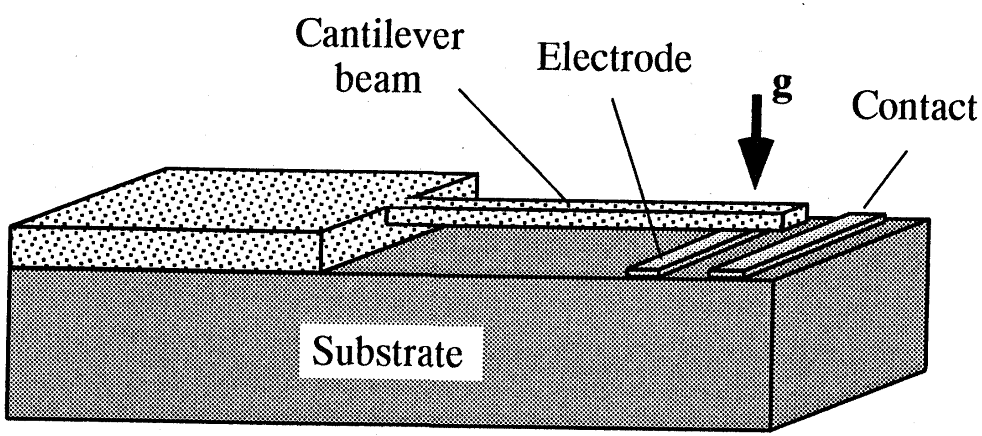




A capacitive accelerometer by Analog Devices

- A mass-produced capacitive accelerometer was presented in 1991
- Microelectronic circuits for signal preamplification, temperature compensation and system self-test were integrated into the sensor
- One of the first successful commercial accelerometers
- Currently used in airbag systems
- Range ±5 g, resolution 0.005 g

Capacitive cantilever microsensor

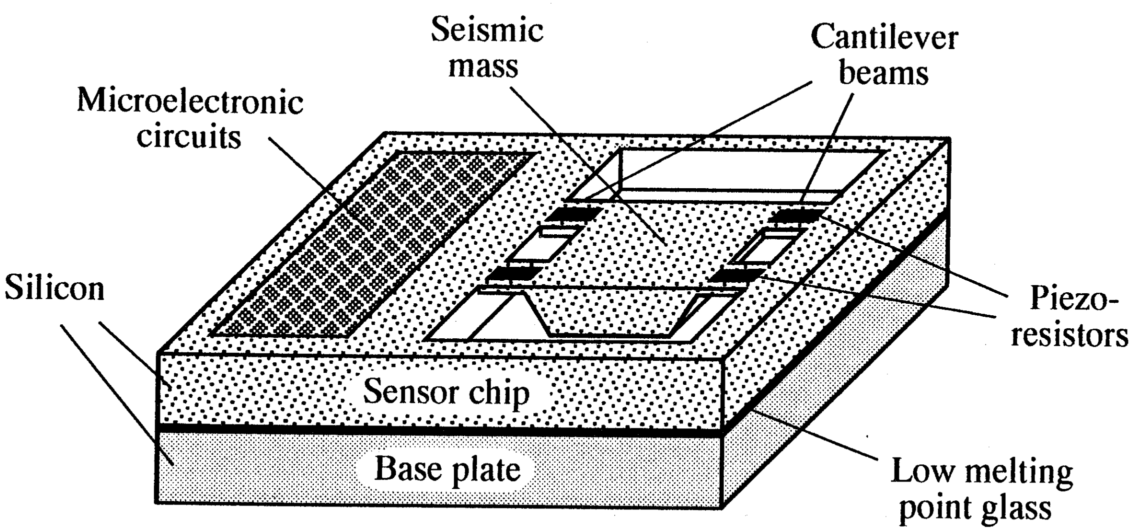


Cantilever length: 120 - 500 µm
Sensitivity: 0.6 - 100 mV/g
Fabrication: dry etching

- Sensor consists of cantilevers acting as one electrode, an electrode strip and a contact strip
- Sawtooth voltage applied to gradually increase the electrostatic force
- Finally cantilever touches the contact strip
- Acceleration affects the magnitude of the voltage that is required for contact

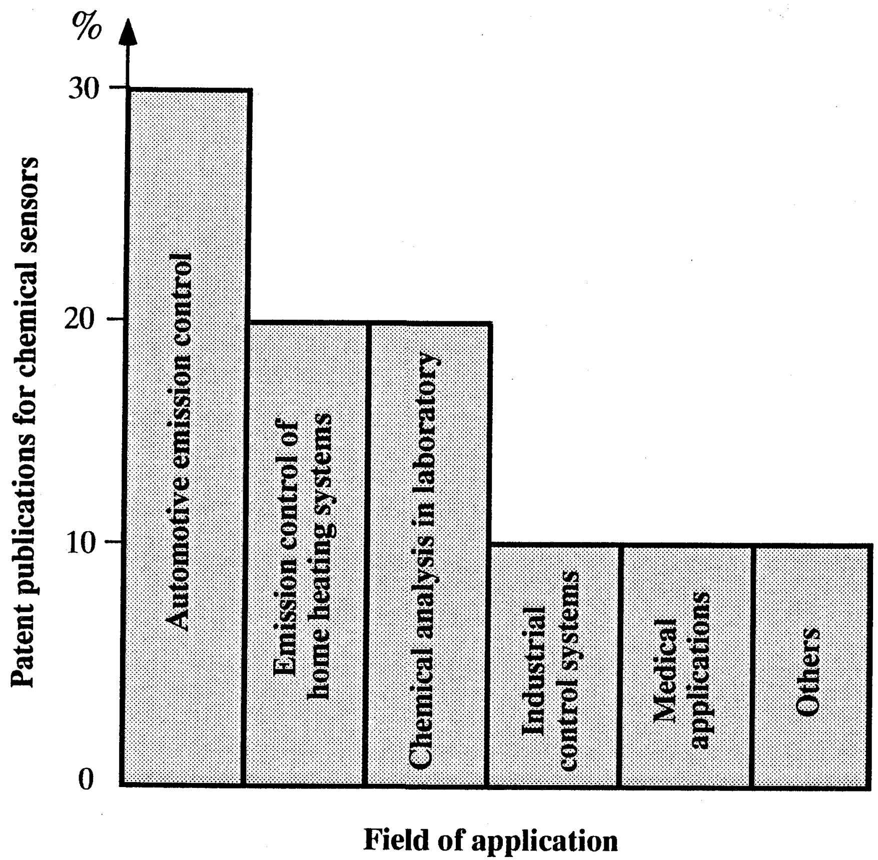
Piezoresistive microsensor with oil damping

- Sensor consists of cantilever beams, a seismic mass and oil.
- Oil dampens the resonance of the suspended mass



Cantilever length: 480 µm
Seismic mass: 2 mg
Fabrication: wet etching

Chemical sensors



- Detect presence or concentration of a chemical substance
- Applications
  - medical diagnostics
  - nutritional science
  - environmental protection
  - automobile industry
- About 60 % of chemical sensors are gas sensors

Chemical sensors ...

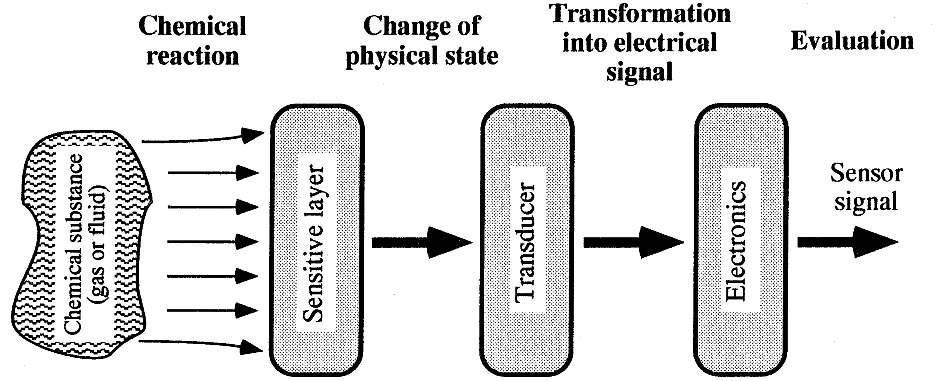
- Conventional measurement methods are often very complicated and expensive, require laboratory conditions, etc.
- Objectives of microsensors:
  - small and inexpensive
  - mass-produced
  - accurate and robust
  - use only small amount of reagents
  - short response times

Chemical sensors ...

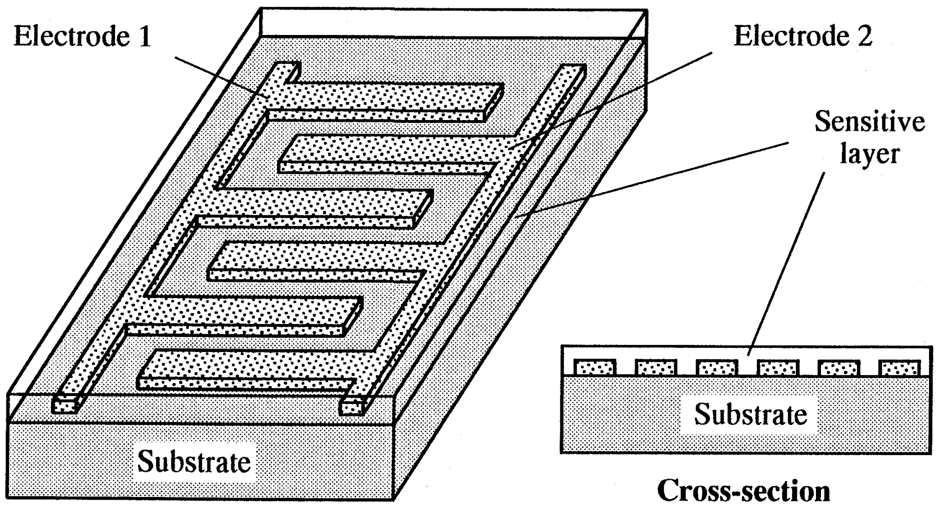
- Research trends (in addition to the development of sensor units):
  - integration of sensors into measurement systems (signal processing)
  - integration of several types of sensors (to test *n* concentrations)
  - microsystems with several identical sensors (local analysis of a substance, distribution of a parameter over a certain domain)
- Sensor principles
  - potentiometer principle in connection with FET
  - acoustic sensors
  - optical sensors

Structure of a chemical sensor system

- A sensitive layer is in contact with the substance
- Chemical reaction occurs on the sensitive layer
- Due to the reaction physical, optical, acoustic or dielectric properties are changed
- Transducer transforms the signal into electrical form



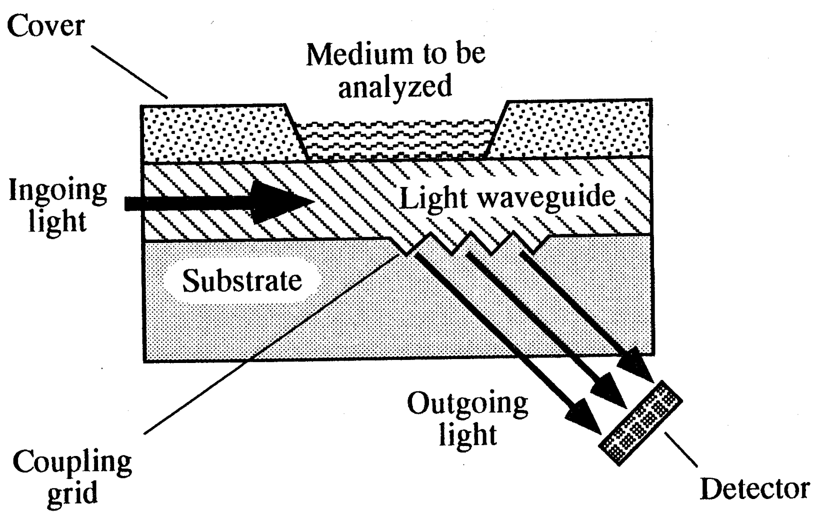
Operation principle of interdigital transducer sensors



- Interdigital transducers using capacitive measurement are often used in chemical sensors
- The capacitance can be adjusted by changing the dielectric properties of the sensitive layer
- E.g. resistance of SnO_2 sensitive layer changes when it interacts with certain substances

$$F_N = \frac{1}{2} eA \left(\frac{U}{d} \right)^2$$

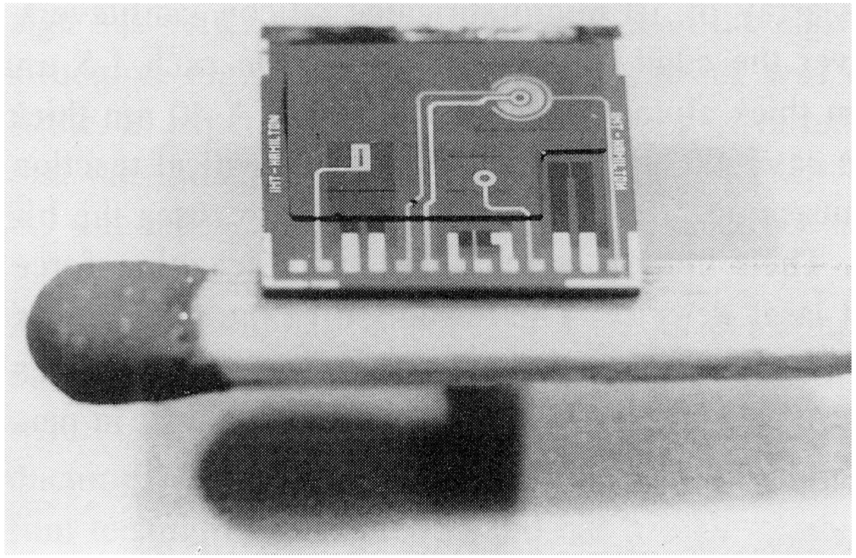
Optical sensor principle



- Optical sensors are inexpensive, easy to sterilize, can handle small samples and are highly sensitive
- Coupling grid detector
  - substance to be analyzed is in direct contact with the waveguide
  - depending on the concentration of the substance its index of refraction varies

  => amount of light striking the sensor depends on the concentration

Ion sensitive FET sensor



Chip size: 10 mm x 10 mm

- For continuous measurement of pH value and gases in blood (O_2, CO_2)
- A device for external use to make on-line diagnosis of a patient
- Consists of a sensor, a blood sampling and processing part
- Uses ion sensitive FET: gate potential is proportional to gas concentration

Biosensors

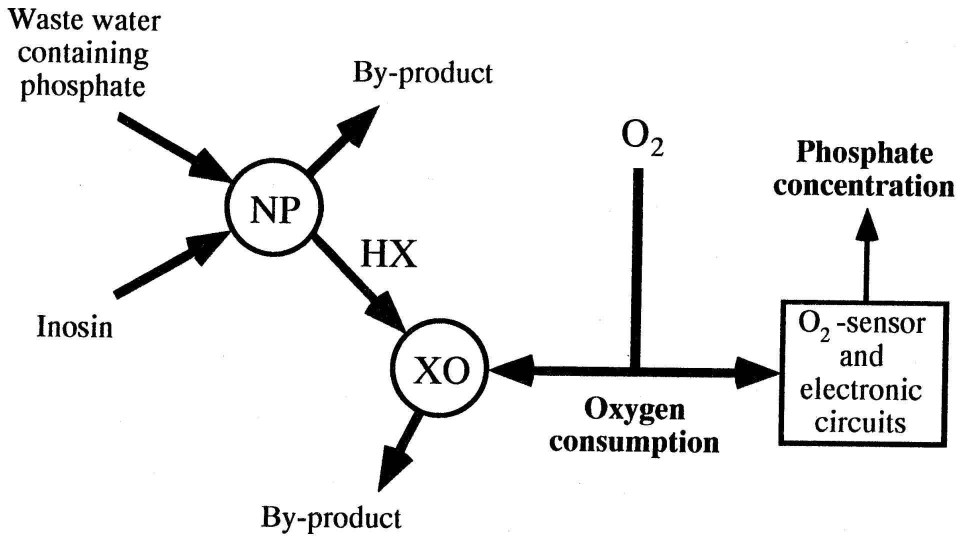
- Measurement principle is similar as with chemical sensors
- Sensitive layer is biologically sensitive, containing e.g. enzymes or antibodies
- Interaction between the molecules of the bioelement and the molecules of the substance changes a physical or chemical parameter
- Parameter change is converted into electrical signal
- Signal represents concentration to be measured

Applications of biosensors

- Biological and nutritional research
  - to detect e.g. heavy metals or allergens
- Medical applications
  - patient data recording for correct and quick diagnosis during surgery

- Integration of biosensors with microfluidic components
  => very small analyzers
- Difficulties
  - immobilization of proteins
  - proteins are not stable for a very long time

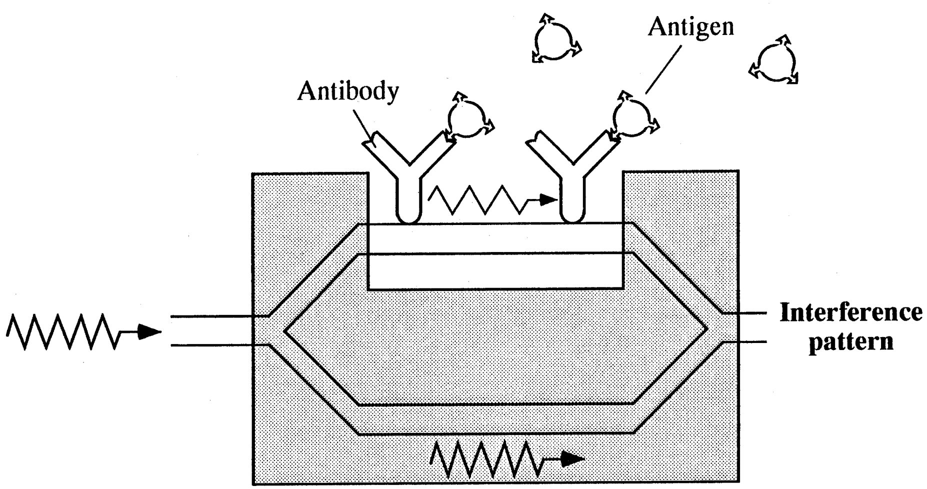
Metabolism sensors



Nucleoside phosphorylase (NP)
hypoxanthine (XP)
xanthine oxidase (XO)

- Uses biosensitive enzymes to catalyze a chemical reaction
- Phosphate measurement
  - enzyme NP detects phosphate and triggers chemical reaction
  - one product of the reaction HX is transformed into XO in another chemical reaction after consuming oxygen
  - amount of oxygen can be measured using a chemical sensor
  - phosphate concentration is proportional to the amount of consumed oxygen

Immuno-sensors



- Antibody is the biosensitive element
- Immobilized antibody molecules bond with antigen molecules in the substance (lock and key)
- The concentration of antigens can be measured using for example interferometric method (light intensity changes)

Temperature sensors

- Important role in monitoring systems
  - process industry
  - medicine
  - environmental protection
- Heating and air conditioning systems
- Indirect measurement of other parameters, e.g. in flow sensors
- Error compensation for temperature dependent sensors and actuators