SENSORS and TRANSDUCERS

Tadeusz Stepinski, Signaler och system

- The Mechanical Energy Domain
  - Physics
  - Surface acoustic waves
  - Silicon microresonators
  - Variable resistance sensors
  - Piezoelectric sensors
  - Capacitive sensors

Mechanical Energy Domain

- Mechanical transducers are used for determination of quantities such as :
  - Position and (angle) displacement
  - Speed, acceleration
  - Weight and pressure
  - Surface flatness
  - Torsion
  - Vibrations

Mechanical Energy Domain - Physics

- Basic physical phenomena used for mechanical transducers :
  - Variable resistance
  - Variable inductance
  - Piezoresistivity effect
  - Piezojunction effect
  - Piezoelectric effect
  - Capacitive effect
  - Surface acoustic waves (SAWs)
  - Microresonators

Mechanical Energy Domain - Physics

- Piezoresistivity

  In 1954 it was discovered that Ge and Si have 100 times higher piezoresistivity than metals.

  Resistivity change of a conductor

$$R' = \frac{l'\rho'}{S'} = \frac{l + \Delta l}{S + \Delta S}(\rho + \Delta\rho)$$

$$\frac{dR}{R} = \frac{d\rho}{\rho} + \frac{dl}{l} - \frac{dS}{S}$$

where:

R' - resistance under pressure

l - length of wire

ρ - resistivity

S - cross section of the wire

Mechanical Energy Domain - Physics

- Piezoresistivity

Poisson ratio = (relative change of diameter)/(relative change in length)

$$n = \frac{dD/D}{dl/l} = \frac{e_D}{e_L}$$

Gauge factor for strain gauges

$$K = \frac{(dR/R)}{e_L} = 1 + 2n + \frac{dr/r}{e_L}$$

Can be understood as the ratio of relative change in resistance and the relative change in length. Often the resistivity, r, is considered a constant and the gauge factor

$$K = 1 + 2n$$

Mechanical Energy Domain - Physics

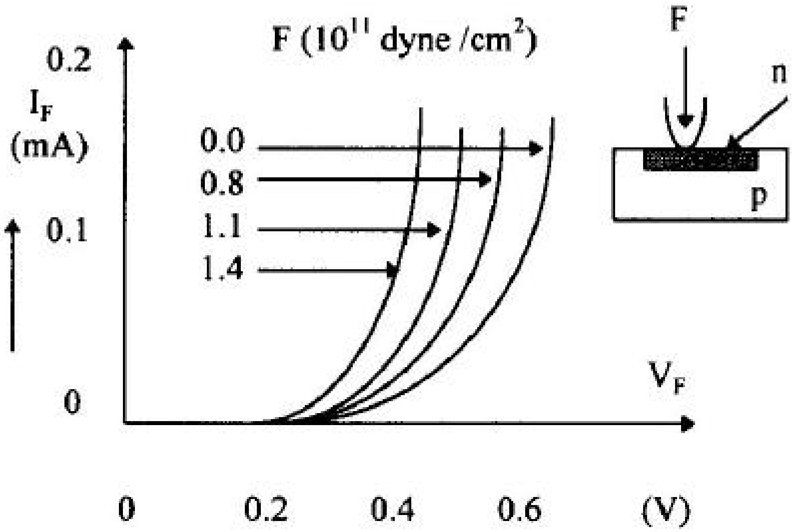
- Piezoresistivity
  - –For metals the K factor is about 2
  - –For silicon K factor is much higher

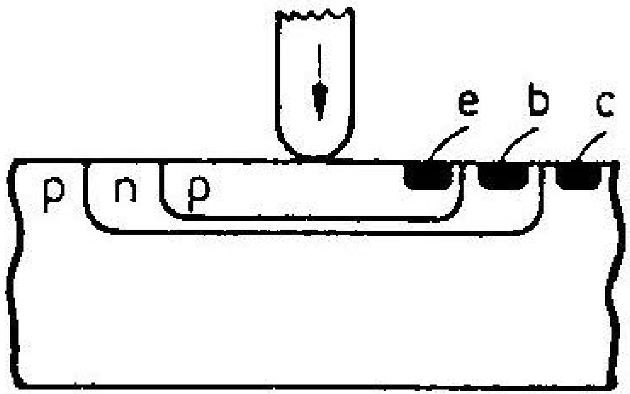
Crystal orientation	n-type Si K factor	p-type Si K factor
[111]	-13	173
[110]	-89	121
[100]	-153	5

  - –Disadvantages of silicon as material for strain gauges:
    - » Brittle material
    - » High temperature coefficient

Mechanical Energy Domain - Physics

- Piezojunction effect
  - A change in I-V characteristic when a p-n junction is subjected to mechanical strain





Mechanical Energy Domain - Physics

- Piezoelectricity
  - –A reversible effect not found in Si and Ge
    - » A voltage connected to the material a mechanical change can be observed
    - » A mechanical force applied to the material an electrical tension can be observed
  - –When piezoelectricity is present in materials there is no centre of symmetry

Crystal structure	**I**	**II**	**III**	**IV**	**V**	**VI**	**VII**
Centrosymmetric				Si^{4+}			
Centrosymmetric				Ge^{4+}			
Acentric			Ga^{3+}		As^{3-}		
Acentric		Cd^{2+}				S^{2-}	
Acentric		Zn^{2+}				O^{2-}	
Centrosymmetric	Na^{+}						Cl^{-}

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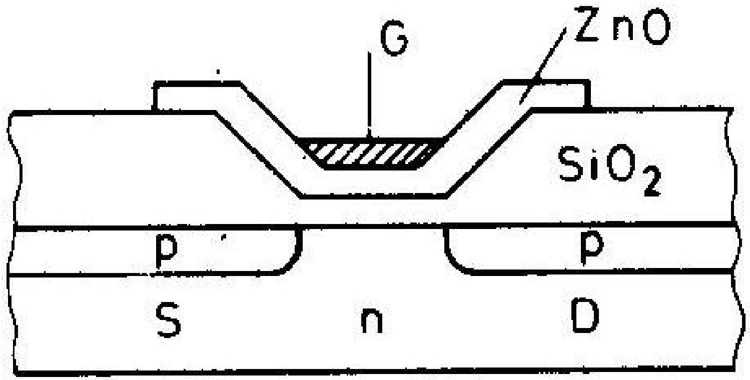
Mechanical Energy Domain - Physics

- Piezoelectricity
  - –Example: PI-DMOS

    Layers of CdS or ZnO are deposited on silicon substrates to obtain pressure transducers



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Mechanical Energy Domain - Physics

- Capacitive effect
  - –A change of capacitance is measured as a function of stress

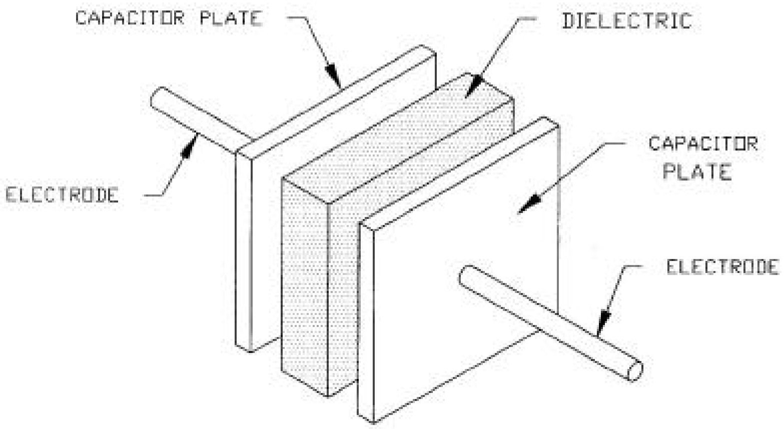
$$C = \varepsilon_r \varepsilon_0 \frac{A}{d}$$

ε_r - relative oermittivity

ε_0 - 8.854 10^{-12} $F\ m^{-1}$

d - distance between the plates m

A - area of the plates m^2



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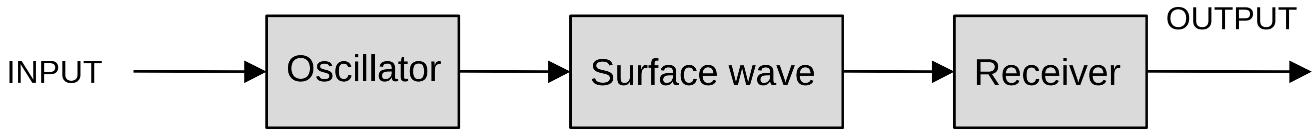
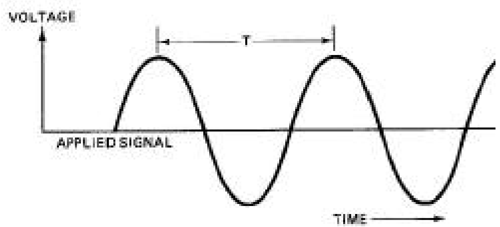
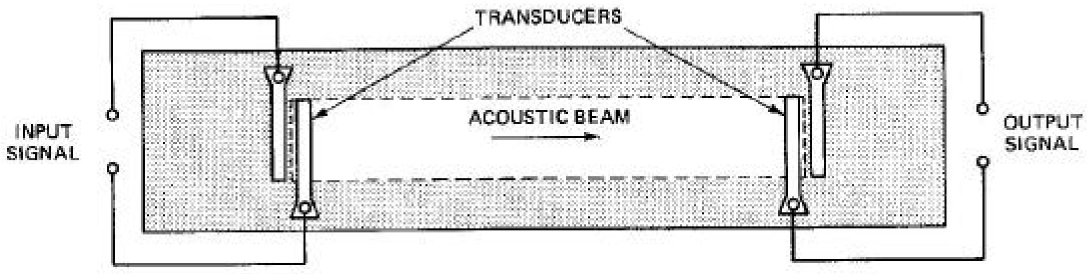
Mechanical Energy Domain - Physics

- Surface acoustic waves (SAW)
  - –Transducers that convert electric signal at the input to an acoustic signal and then again to an electrical signal at the output







(a)

Metal film deposed on the piezoelectric substrate

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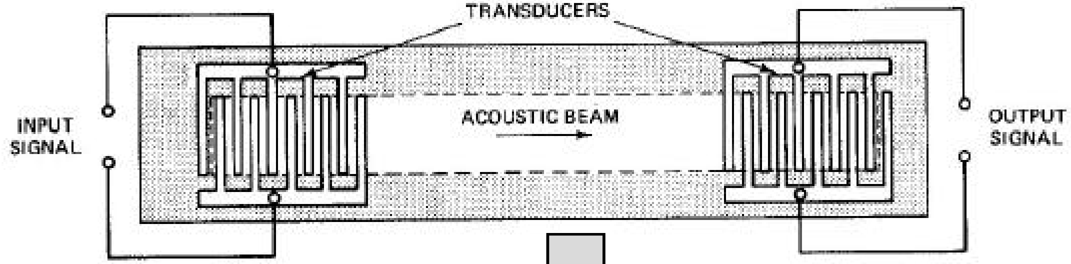
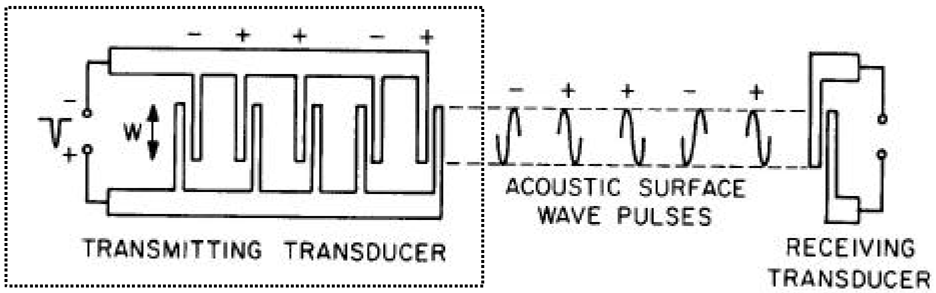
Surface Acoustic Waves

- Surface acoustic waves (SAW)
  - Multiple electrodes tuned to the same frequency generate Reyleigh wave
  - Substrate lithium niobiate



Digitally coded SAW filter



Surface Acoustic Waves

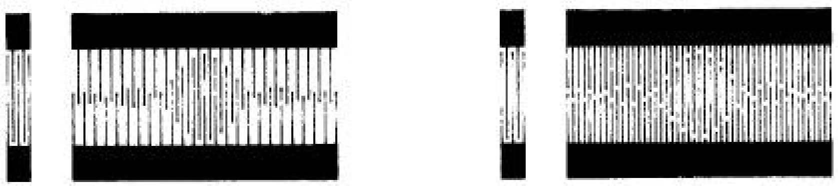
- Surface acoustic waves (SAW)

  Standard **uniform transducer** has N fingers with constant length and uniform finger pair spacing. Its frequency response takes the form of *sinc(x)*

$$|H(x)| \approx 2\gamma N \cdot \left|\frac{\sin x}{x}\right| \quad where \quad x = \frac{N\pi(\omega - \omega_0)}{\omega_0}$$

  ω_0- center frequency of the transducer

  Apodized transducer - by tapering the length of fingers and their spacing, the spectral response of the transducer can be tailored to any given characteristic.



(a) (b)

Microresonators

- Silicon microresonators
  - Resonant microsensor (microresonator) - a device with a mechanical element at resonating frequency which outputs the resonance frequency changes as a function of a physical or chemical parameter.
  - Microresonators take the form of cantilevers, micro tuning forks and diaphragms
  - Center frequency of cantilever

$$f = 0.16 \cdot \frac{t}{l^2} \cdot \sqrt{\frac{E}{\rho}}$$

where: l, t (m) - length respective thickness of the tongue

E (Pa) - modulus of elasticity

ρ (kgm^{-3}) - specific mass

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Mechanical Energy Domain - Microresonators

- Microresonator types
  - Vibrating strings
  - Vibrating beams
  - Vibrating capsules
- Excitation and detection in silicon microresonators can be performed in different ways:
  - »Electrostatic excitation - two electrodes in close proximity
  - »Piezoelectric excitation- built-in piezoelectric material
  - »Resistive heating excitation - integrated diffused resistor
  - »Optical heating excitation - periodically activated laser
  - »Magnetic excitation - electric current + magnetic current

Variable-resistance sensors

- Potentiometers

  Sensing position and angle

- Strain gauges

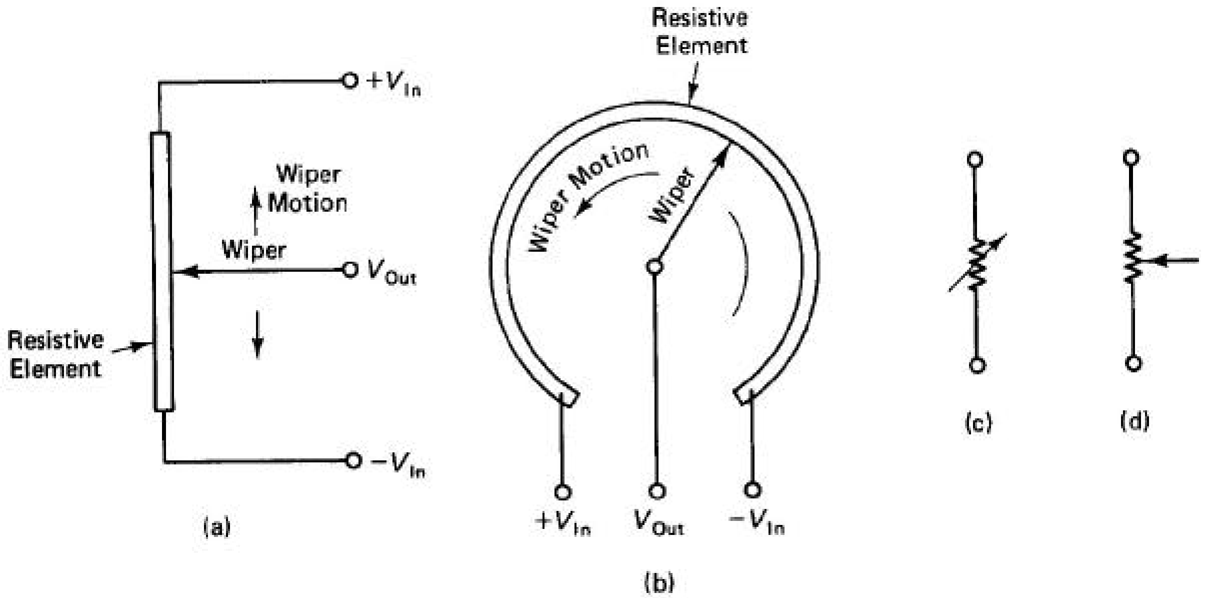
  Sensing strain and pressure

Voltage divider rule:

$$E_{out} = r \cdot I_T = r \cdot \frac{E_s}{R + r}$$

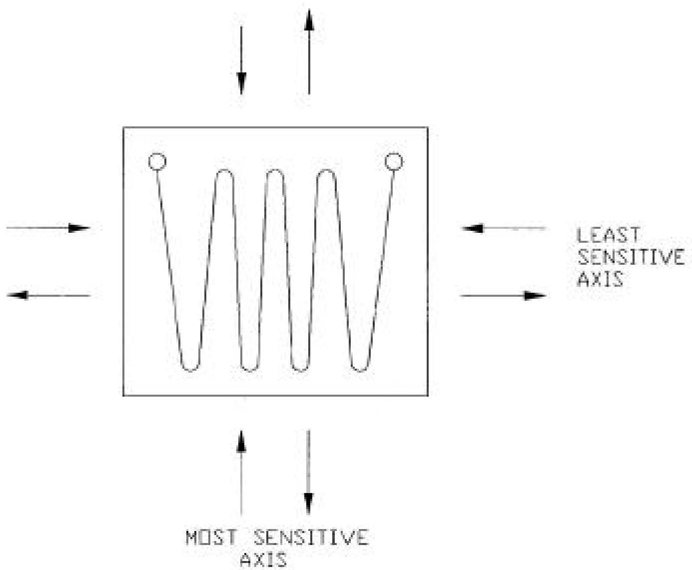
Variable-resistance sensors

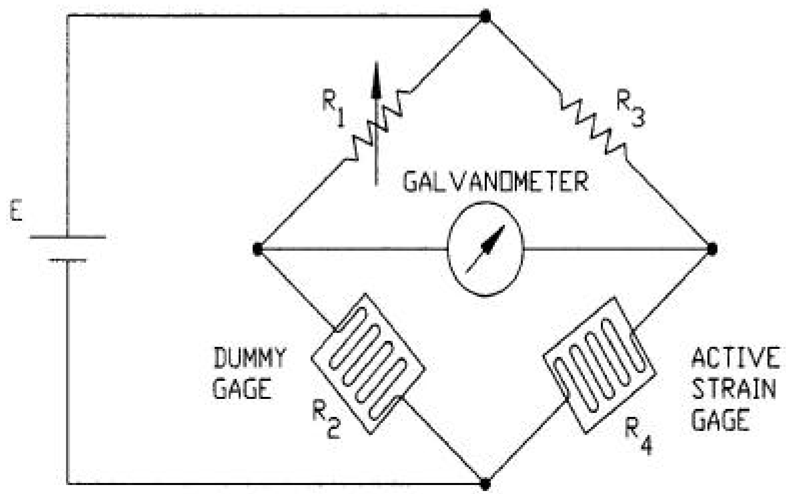
- Potentiometers



Variable-resistance sensors

- Strain gauges
  - Principle





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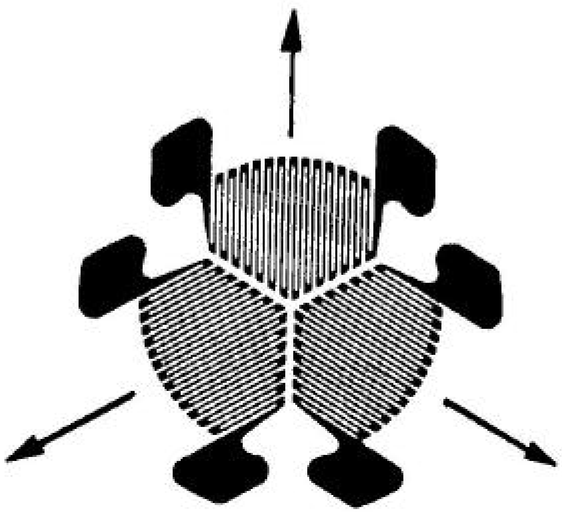
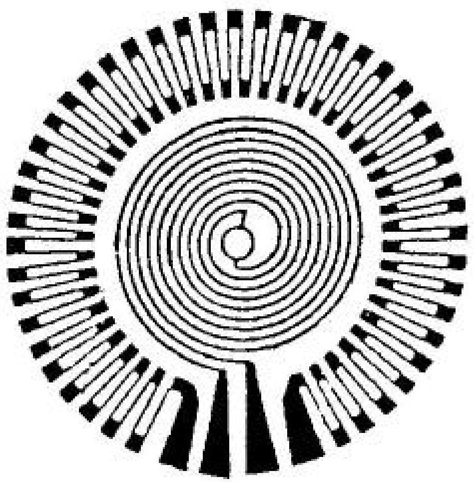
Variable-resistance sensors

- Strain gauges
  - Practical realization

Strain measurement - 3 axes



Pressure measurement



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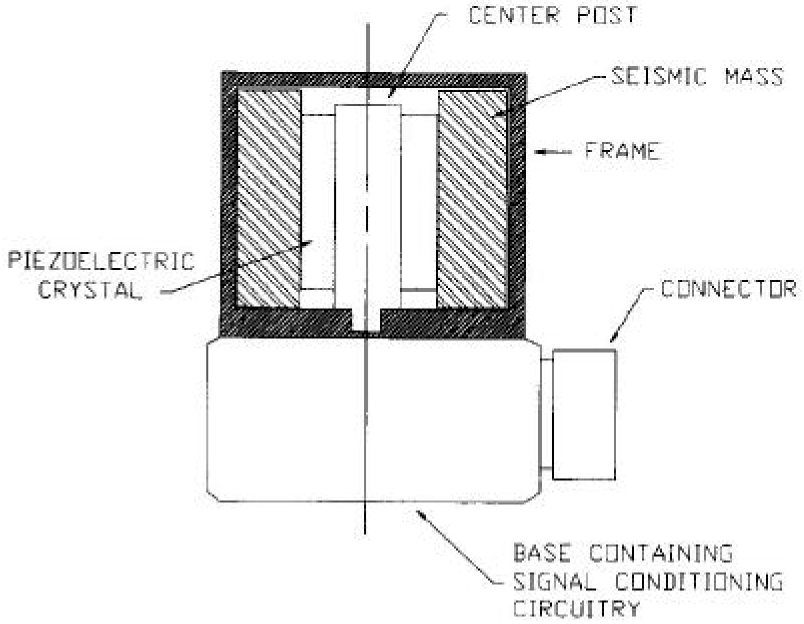
Piezoelectric sensors

- Crystal Accelerometers



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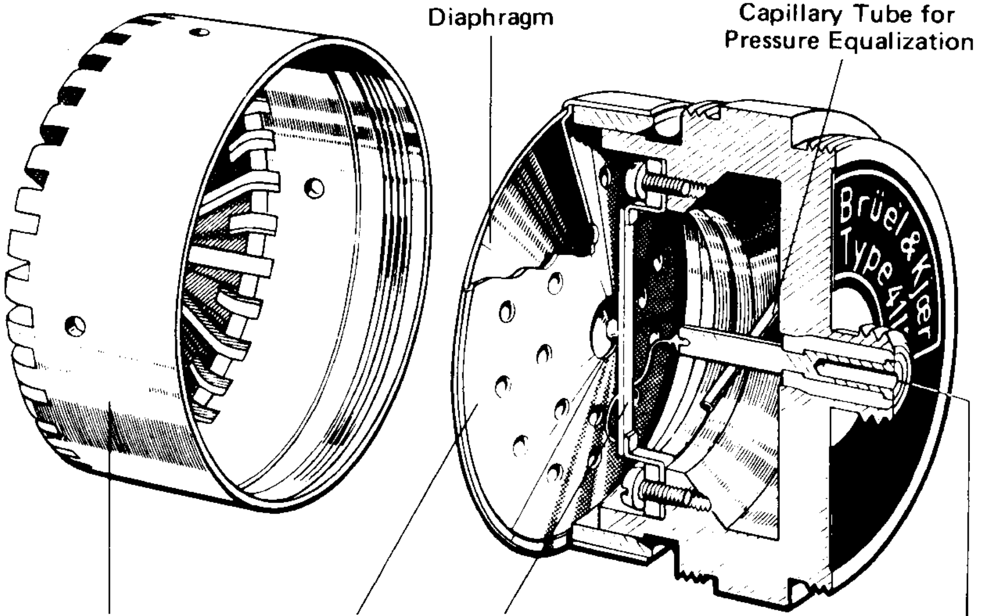
Piezoelectric sensors

- Piezoelectric microphone

  Ceramic bender is made of piezoelectric material PZT (lead ziroconate titanate)

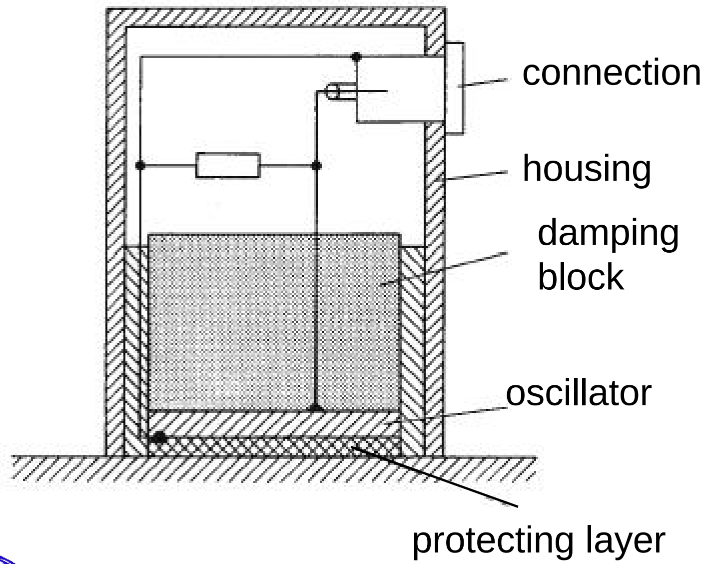


(a)

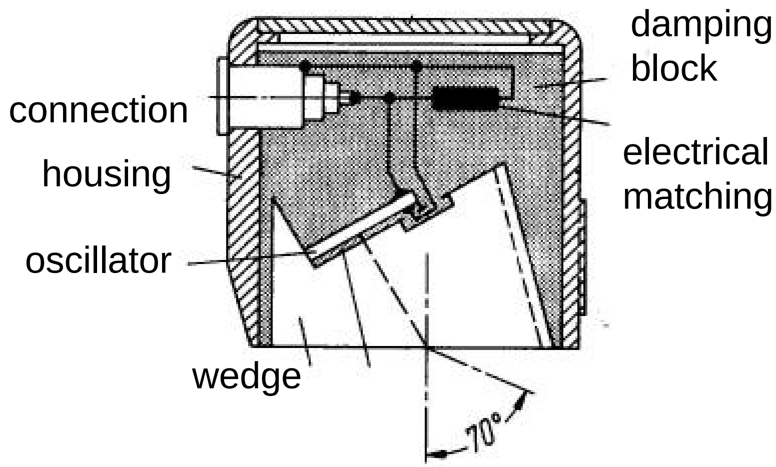
Piezoelectric sensors

- Piezoelectric ultrasonic transducers for nondestructive evaluation of materials

Normal contact transducer



Angle transducer



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Variable-capacitance sensors

- Principle

$$C = \frac{e \cdot A}{d}$$

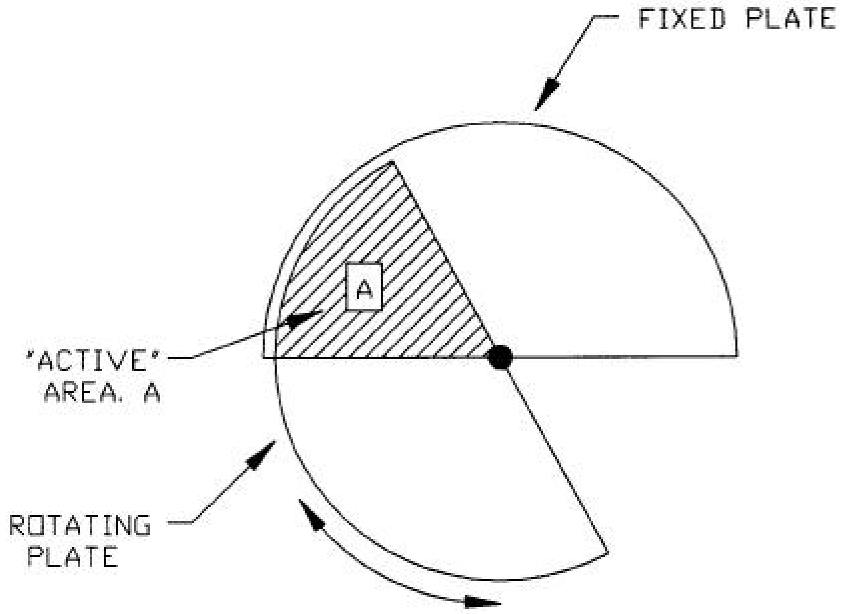
where:

C - capacitance (F)

ε - permitivity (F/m)

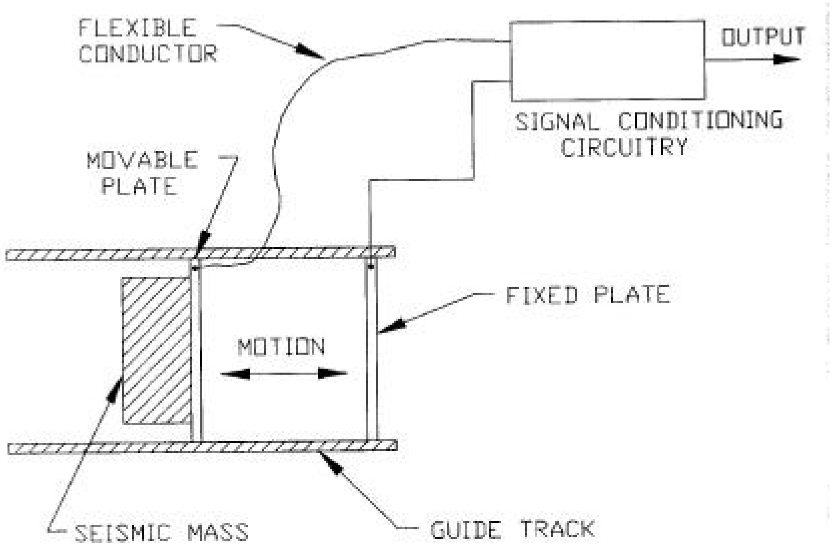
A - area (m^{2})

S - separation distance of plates (m)



Variable-capacitance sensors

- Applications
  - Seismic mass for detecting acceleration



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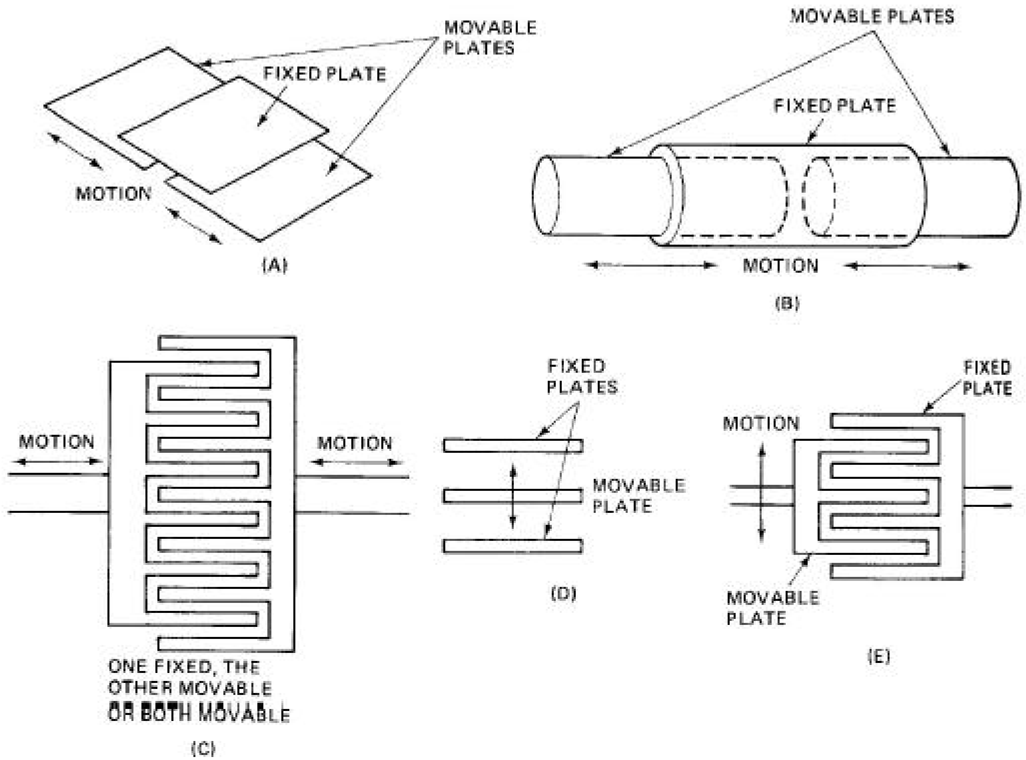
Variable-capacitance sensors

- Applications
  - Linear displacement detectors



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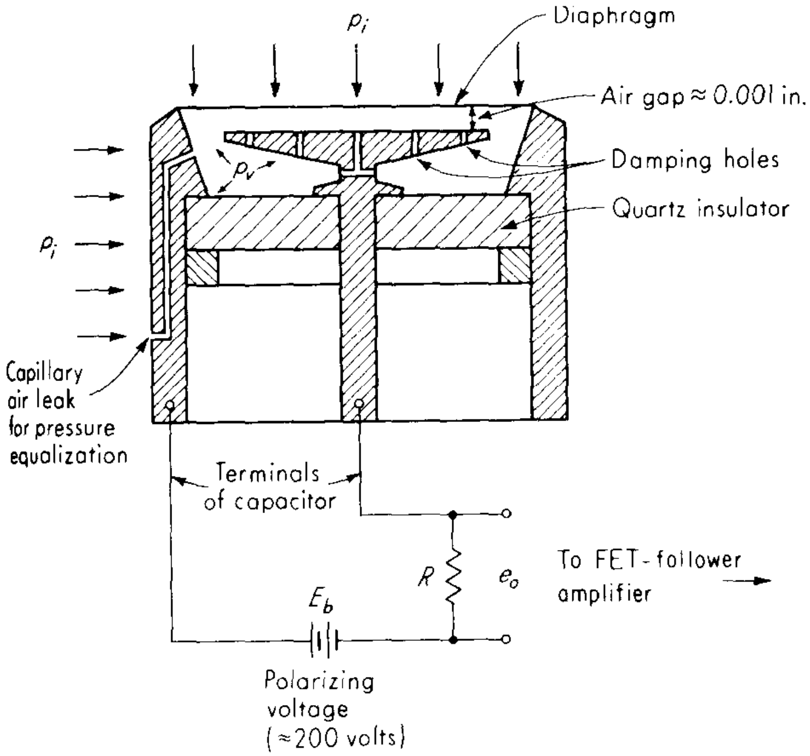
Variable-capacitance sensors

- Applications
  - Capacitor microphone



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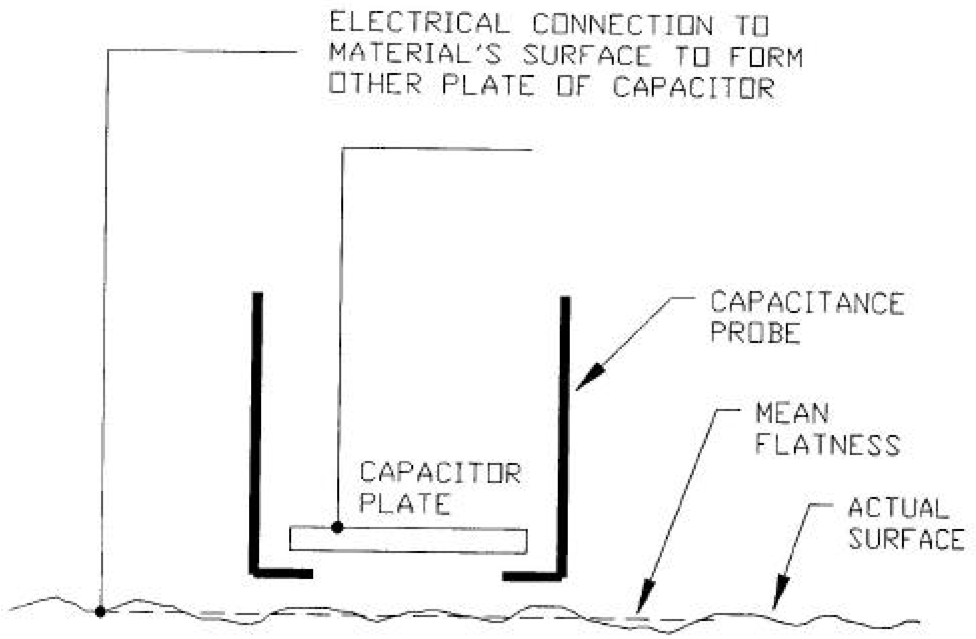
Variable-capacitance sensors

- Applications
  - Surface roughness detection



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Review Questions

- Describe one application of piezojunction effect
- Explain in detail how SAW filter operates
- What is a strain gage? Explain how it works and give an example of an application
- Explain the function of a dummy gage in a strain gage setup
- Describe at least two types of mechanical construction techniques used in making linear capacitive sensors
- What advantage is there is using multiple-plate capacitive sensors rather than single-plate sensors?
- Explain in detail how a piezoelectric substance is used in conjunction with seismic mass to produce accelerometer
- If quartz and piezoelectric crystal are not electrically conductive, explain how it appears that a current is "conducted through" these substances at their resonant frequencies.