Electromechanical Sensors and Actuators

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Lecture 1
Introduction and Transducer Models

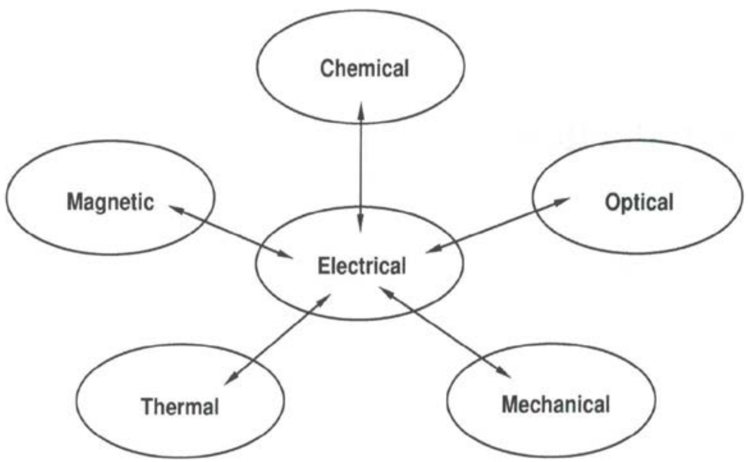
- **Definition of transducers**
- **Sensors and actuators**
- **Categories of sensors and actuators**
- **Analog system**

What is a Transducer?

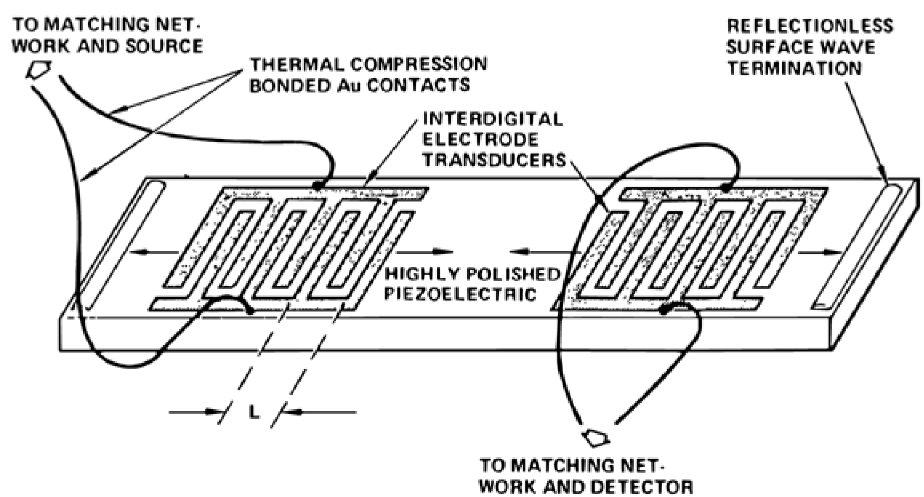
There are many definitions of transducers in use:

Definition 1

- A transducer is a device which transforms non-electrical energy into electrical energy or vice versa



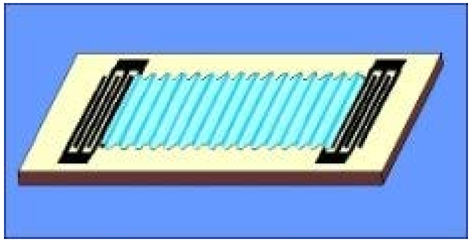
Surface Acoustic Wave (SAW) Devices

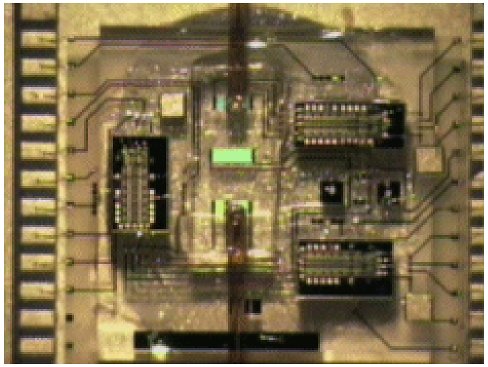


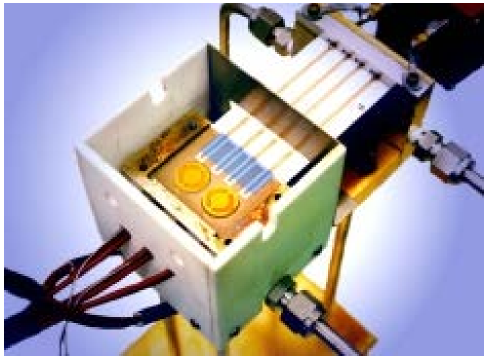
Example 1:
Acoustic Wave Transducers

- **Bulk acoustic wave (BAW) and surface acoustic wave (SAW)-Based transducers:**

  Transducers based on BAW and SAW devices are being developed for a wide range of transducer applications. The devices is an extremely sensitive gravimetric detector that can be coated with a film to collect chemical species of interest. Based on these devices, sensor systems have been developed that can detect trace (ppm to ppb) levels of airborne contaminants. Applications include combustible gas sensor, pressure sensors, temperature sensors, weapon state-of-health, environmental, and non-proliferation monitoring.



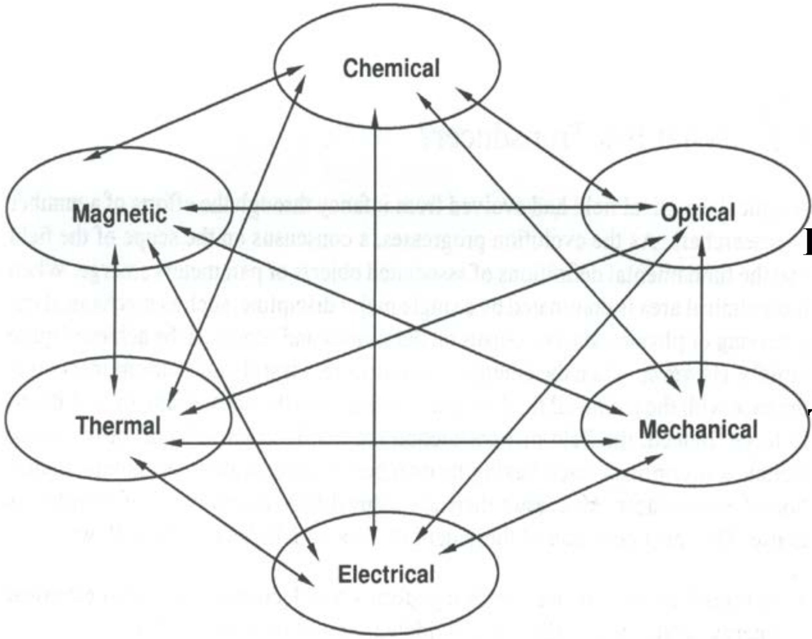




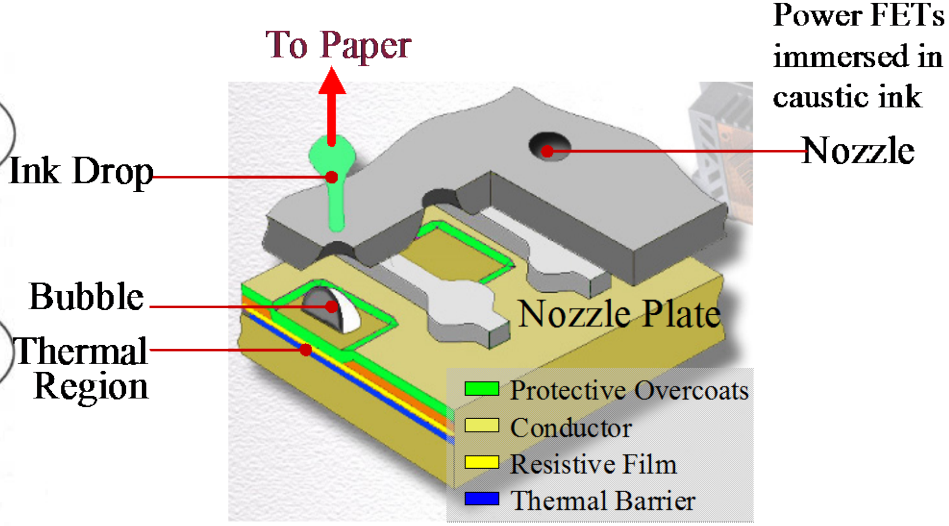
What is a Transducer?

Definition 2

- A transducer is a device which transforms energy from one domain into another. Typical energy domains are mechanical, electrical, chemical, fluid, and thermal



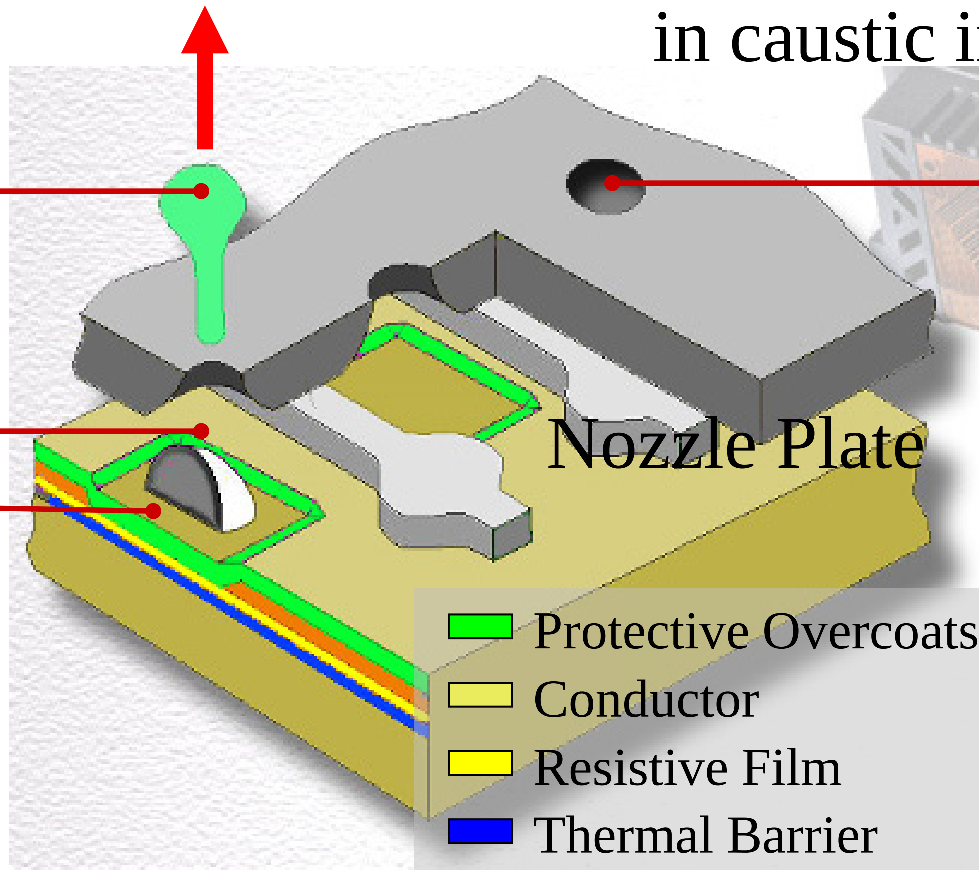
Example —Thermal Actuator :
Thermal Ink Jet Printheads

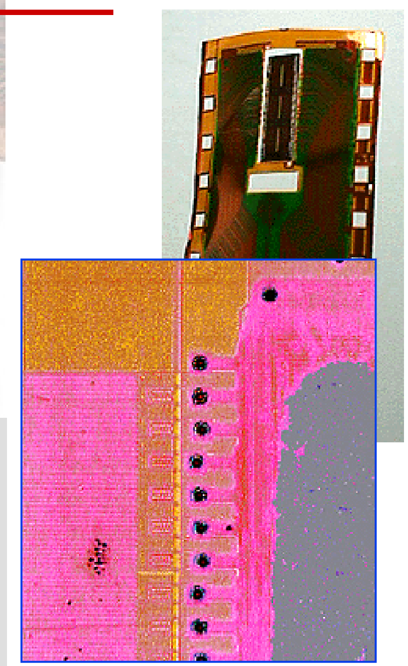


Example 2

Thermal Inkjet Printhead

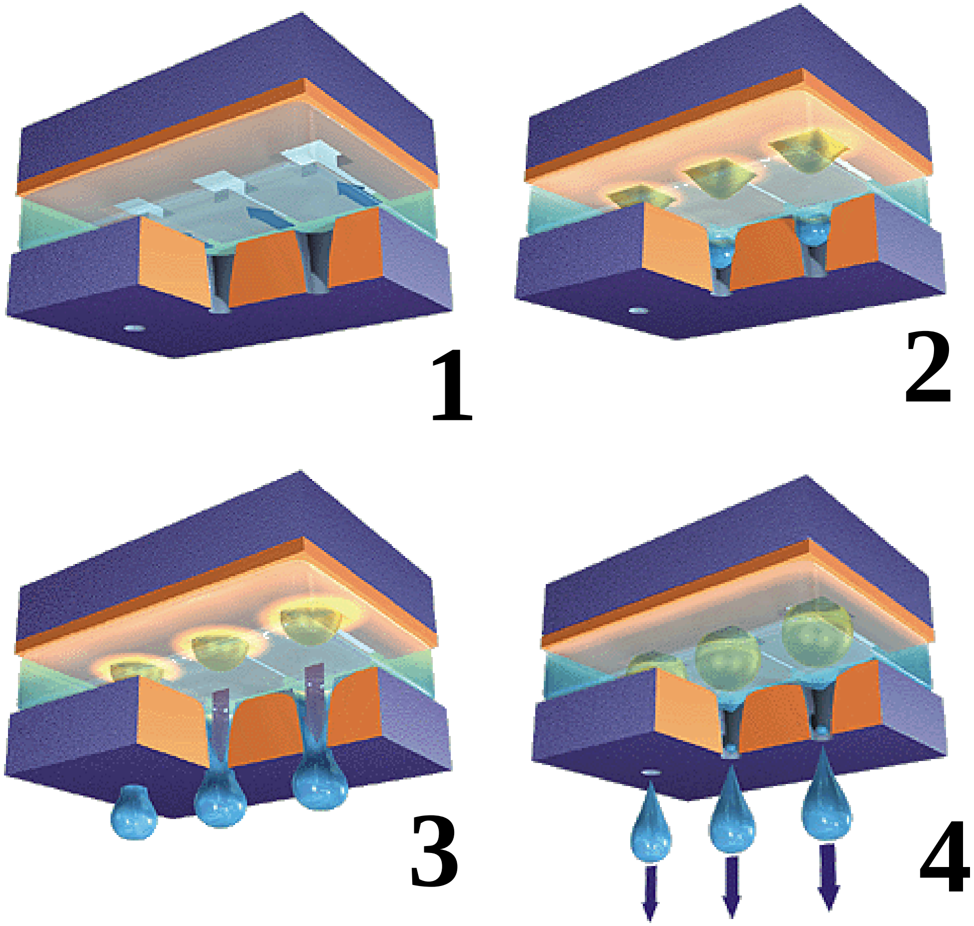
Example 2
Thermal Inkjet Printhead





Example 2
Thermal Inkjet Printhead

Thermal - Bubble Formation



STEP1: Initial conditions

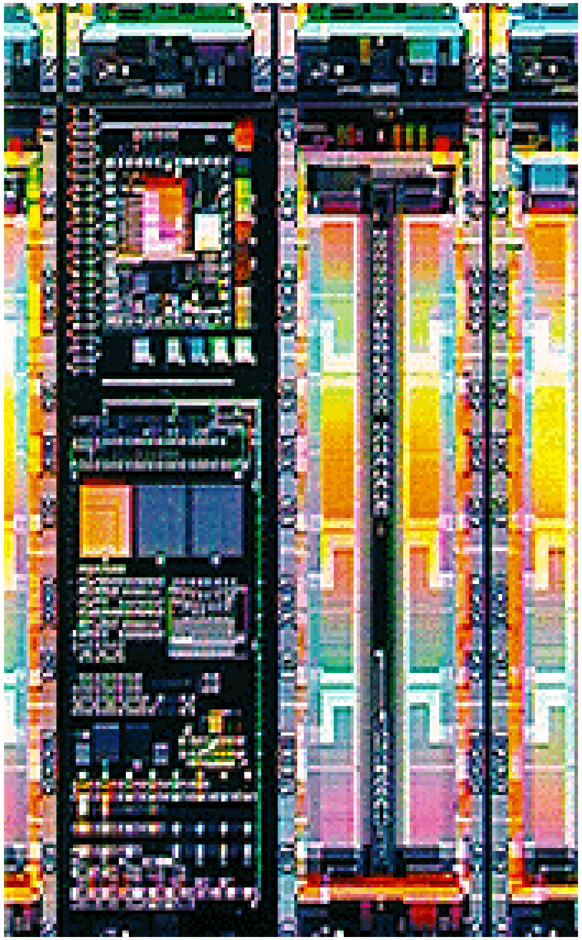
STEP2: Resistor heated upon command and liquid vaporizes instantly causing a vapor bubble to form.

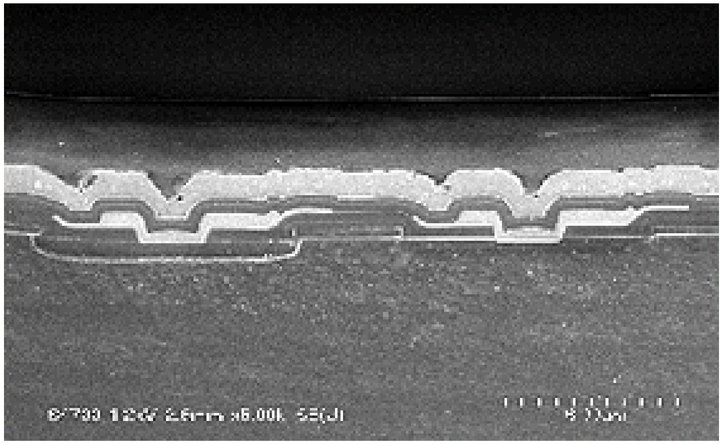
STEP3: Vapor bubble grows to maximum size and ink ejected out of nozzle.

STEP4: The bubble collapses and breaks off. Nozzle returns to initial condition.

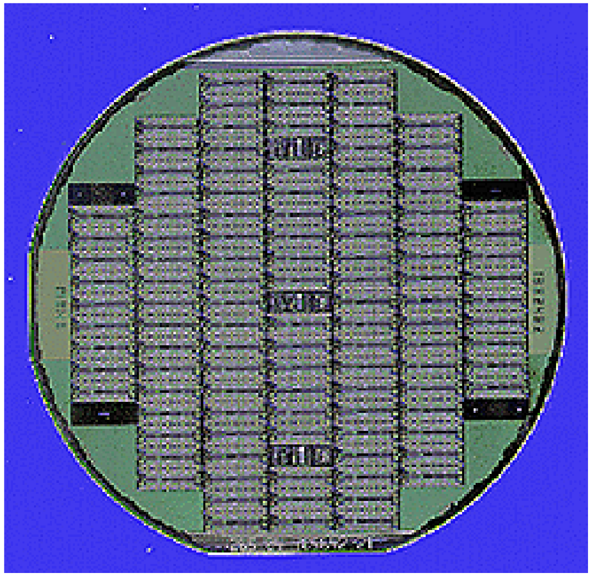
Example 2
Thermal Inkjet Printhead

A Semi Conductor Technology





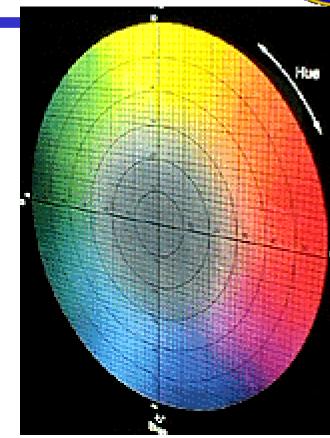
Layers



Example 2
Thermal Inkjet Printhead

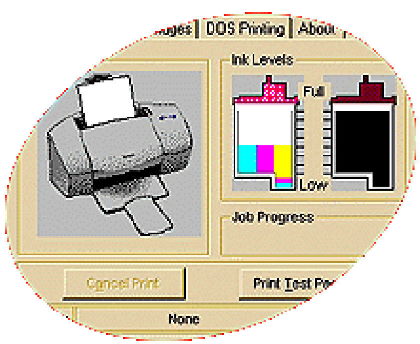
Inkjet Printhead

TECHNOLOGIES



INK

PRINTHEAD

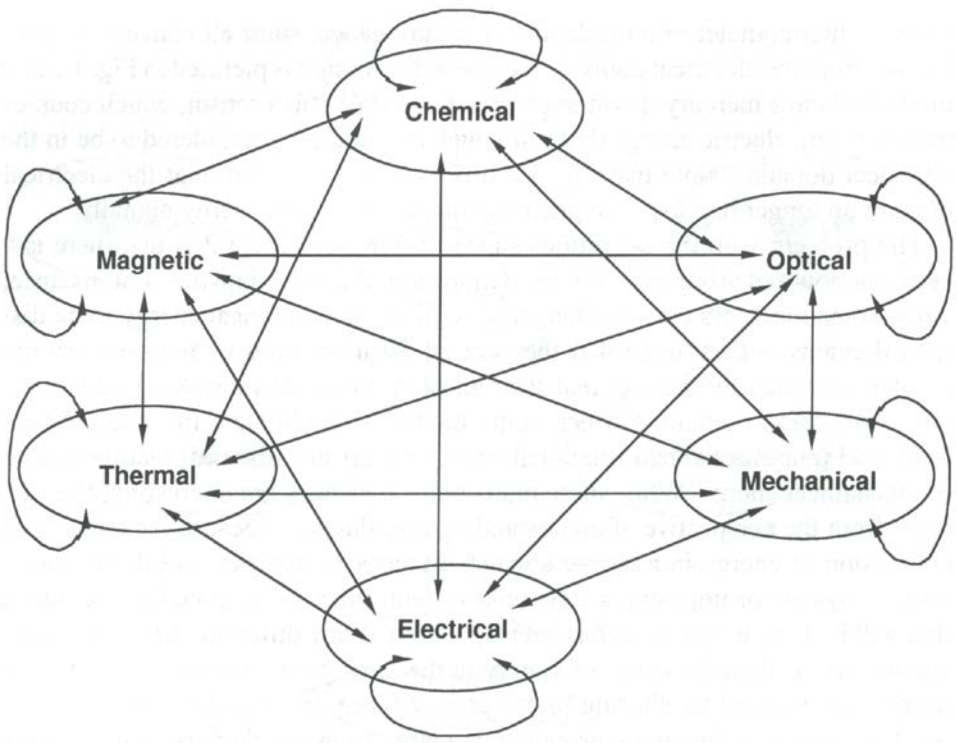


DRIVER

What is a Transducer?

Definition 3

- A transducer is a device which transforms energy from one type to another, even if both energy types are in the same domain



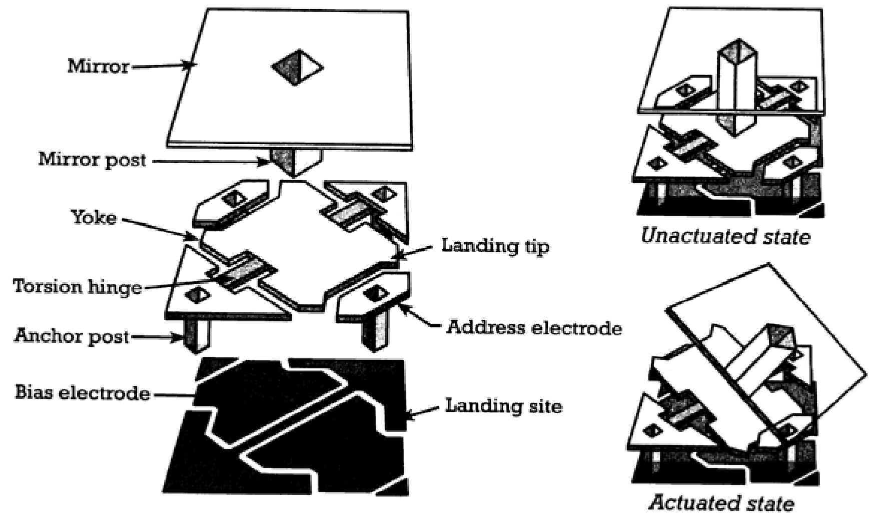


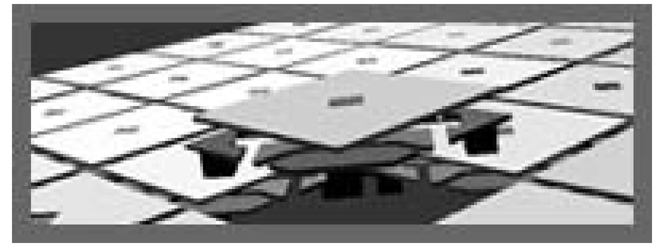
Figure 4.29 Illustration of a single DMD™ pixel in its resting and actuated states. The basic structure consists of a bottom aluminum layer containing electrodes, a middle aluminum layer containing a yoke suspended by two torsional hinges, and a top reflective aluminum mirror. An applied electrostatic voltage on a bias-electrode deflects the yoke and the mirror towards that electrode. A pixel measures approximately 17 μm on a side. Adapted from Van Kessel et al. [26].

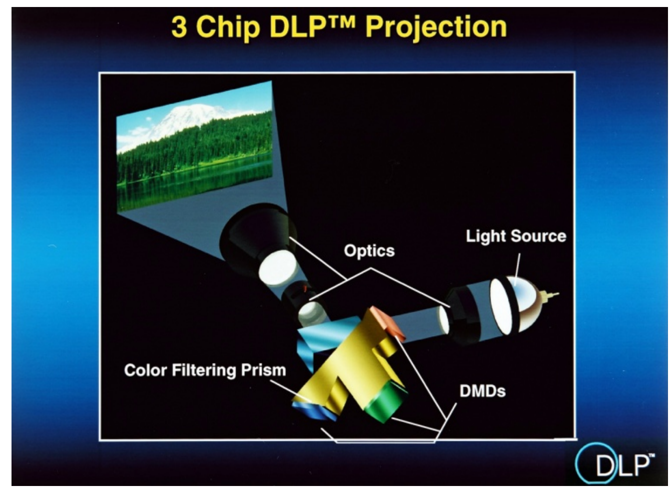
Example 3: DMD devices for display

- The **Digital Micromirror Device**, or DMD chip, which was invented by Dr. Larry Hornbeck of Texas Instruments in 1987.

  The DMD chip is probably the world's most sophisticated light switch. It contains a rectangular array of up to 1.3 million hinge-mounted microscopic mirrors; each of these micromirrors measures less than one-fifth the width of a human hair.

  When a DMD chip is coordinated with a digital video or graphic signal, a light source, and a projection lens, its mirrors can reflect an all-digital image onto a screen or other surface. The DMD and the sophisticated electronics that surround it are what we call **Digital Light Processing™ technology**.

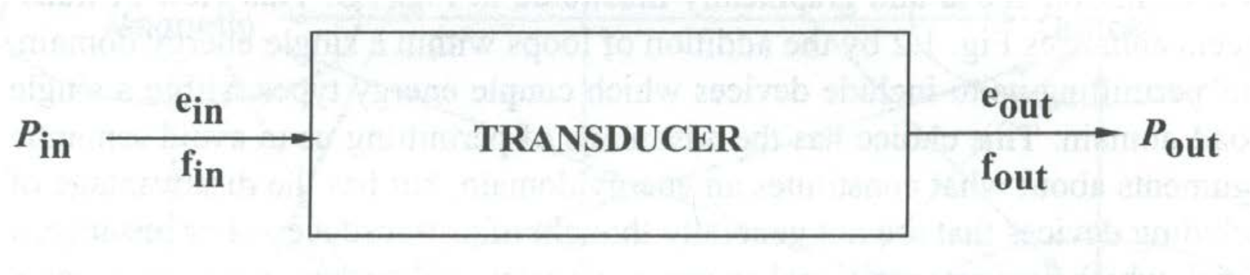




http://www.dlp.com/dlp_technology/dlp_technology_overview.asp

What is a Transducer?

- **General view of a transducer: a 2-port device**



  - P_{in} is the input power
  - f and e are two power conjugate variables which when multiplied yield the power in a given energy domain, such as a voltage and a current for an electrical port, or a force and a velocity for a mechanical port
  - P_{out} is the output power
  - The ratio analogous to the electrical impedance (voltage/current) is defined as the impedance

- **We can define a transducer as a multiport device in which the input impedance(s) is (are) not equal to the output impedance(s)**

What is a Transducer?

- **Examples:**

  P=V•I=Voltage •Current

  P=F •v=Force •Velocity

- **Using the two conjugate power variables (time-dependent): an effort *e(t)* and a flow *f(t)*, the time-dependent generalized displacement *q(t)* is given by**

$$q(t) = \int_{t_0}^{t} f(t)\, dt + q(t_0)$$

- **The time-dependent generalized moment *p(t)* is given by**

$$p(t) = \int_{t_0}^{t} e(t)\, dt + p(t_0)$$

- **Examples of conjugate power variables**

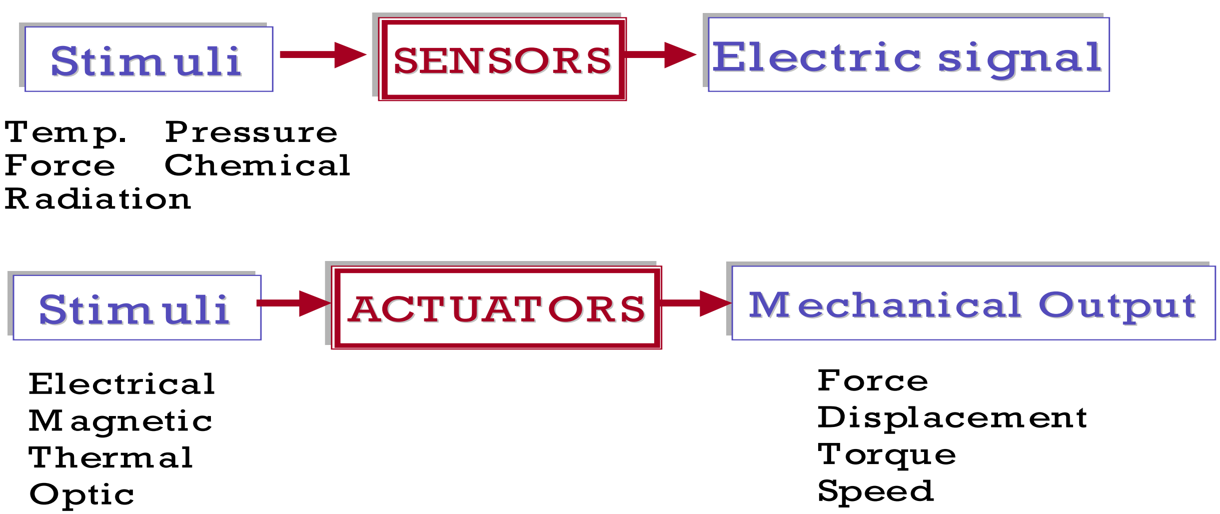
Energy Domain	Effort	Flow	Momentum	Displacement
Mechanical translation	Force F	Velocity $\dot{x}, v$	Momentum p	Position x
Fixed-axis rotation	Torque τ	Angular velocity ω	Angular momentum J	Angle θ
Electric circuits	Voltage V, v	Current I, i	...	Charge Q
Magnetic circuits	Magnetomotive force MMF	Flux rate $\dot{\phi}$	...	Flux ϕ
Incompressible fluid flow	Pressure P	Volumetric flow Q	Pressure momentum Γ	Volume V
Thermal	Temperature T	Entropy flow rate $\dot{S}$	...	Entropy S

Why Study Transducers?

- Exponential growing number of transducers being found in common products
- The success of the conversion of electronics to microelectronic circuits
  - Most transducers have at least one electrical port and are packaged with significant electronics attached
  - Transducers are normally the weak link in a system, and the gap between transducers and processing electronics in terms of reliability, cost, and power is increasing at an alarming rate
- Escalating demand for automatic control of processes
  - All control need actuators and, if the control is closed-loop, sensors are needed as well
- The development of new materials and techniques
  - Materials capable of converting one form of energy to another is the heart of many transducers

Division of Transducers into Sensors and Actuators

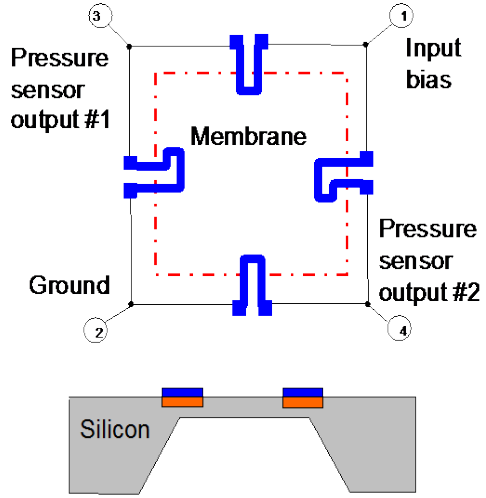
- Transducers may generally be divided into two class
  - Sensors, which monitor the system
  - Actuators, which impose a condition on a system
- Sensors and actuators are comprehensive classes of transducers
- Some transducers can operate as a sensor or as a actuator, but not as both simultaneously



Sensors and Actuators

- Sensor examples:
  - Hot-wire anemometers (measure flow velocity)
  - Microphones (measure fluid pressure)
  - Accelerometers (measure the acceleration of a structure)
  - Gas sensors (measure concentration of specific gas or gases)
  - Humidity sensor
  - Temperature sensors, etc.

Bulk micromachined, piezoresistive pressure transducer, rated to 100psi:

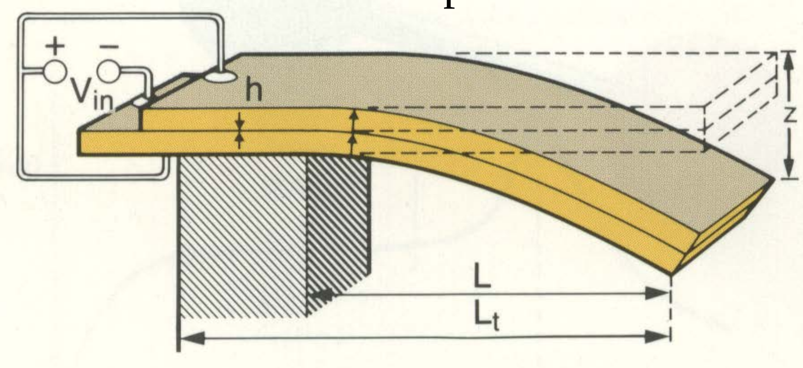


- Ideally, a sensor monitor a parameter of a system without disturbing that parameter.
- We can minimize the effect of a sensor on the system by minimizing the energy exchange. For this reason, most sensors are low power, and small devices. Exactly what constitutes *small* or *low power* depends on the particular situation.

Sensors and Actuators

- Actuator examples
  - Motors (which impose a torque)
  - Force heads (which impose a force)
  - Pumps (which impose either a pressure or a fluid velocity)

Bimorph actuator



Cantilever mounted parallel bimorph

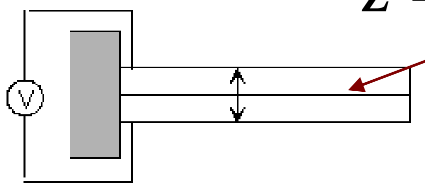
- Ideally, actuators impose a state on a system that is independent of the load applied to them. In reality, this can never be achieved for a transducer with finite energy, because there will always be a load which exceeds its energy handling ability.
- The desire to minimize the effect of the load imposed by the system on the actuator performance usually leads to large, high power actuators. Exactly what constitutes *large* or *high power* depends on the particular circumstances.

Example 3

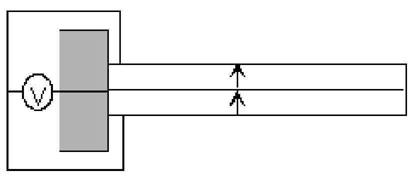
Piezoelectric Actuators

Piezoelectric Cantilever Actuators

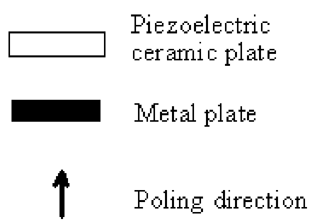
$$z = \frac{3d_{31}L^2}{2t^2}V \qquad F_{bl} = -\frac{3d_{31}wt}{8s_{11}^E L}V$$

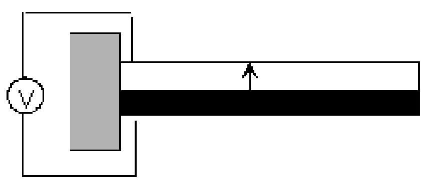


(a) Bimorph in series connection

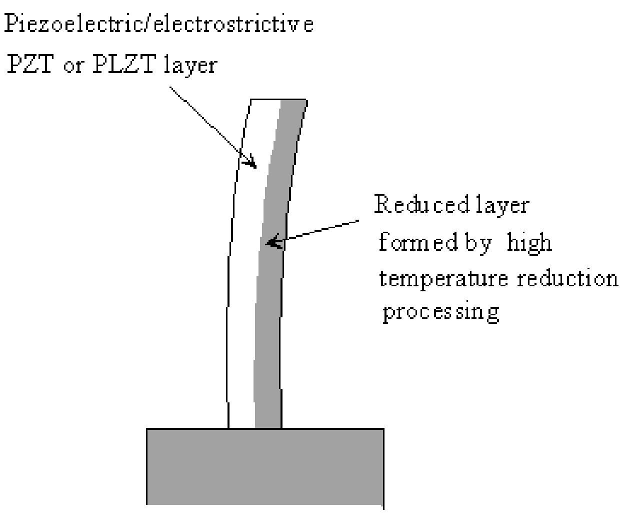


(b) Bimorph in parallel connection



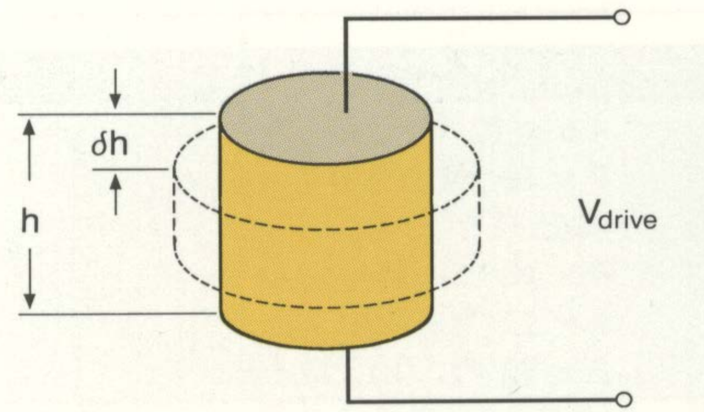


(c) Unimorph

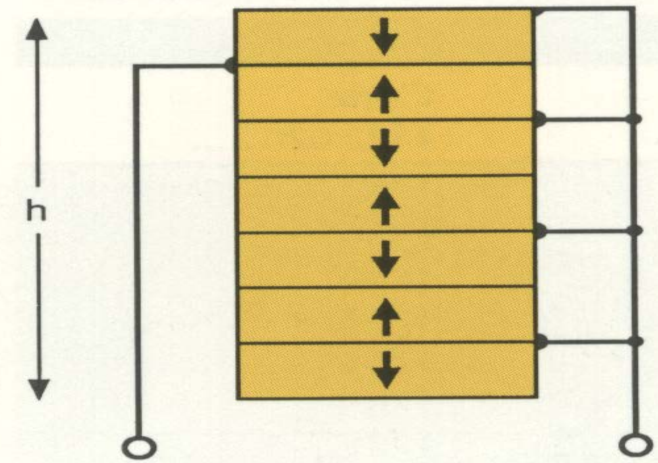


(d) RAINBOW actuator

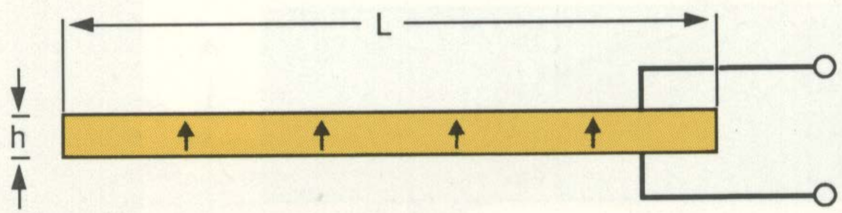
Piezoelectric multilayer actuators



Actuator action of a PXE body



Stack of PXE discs



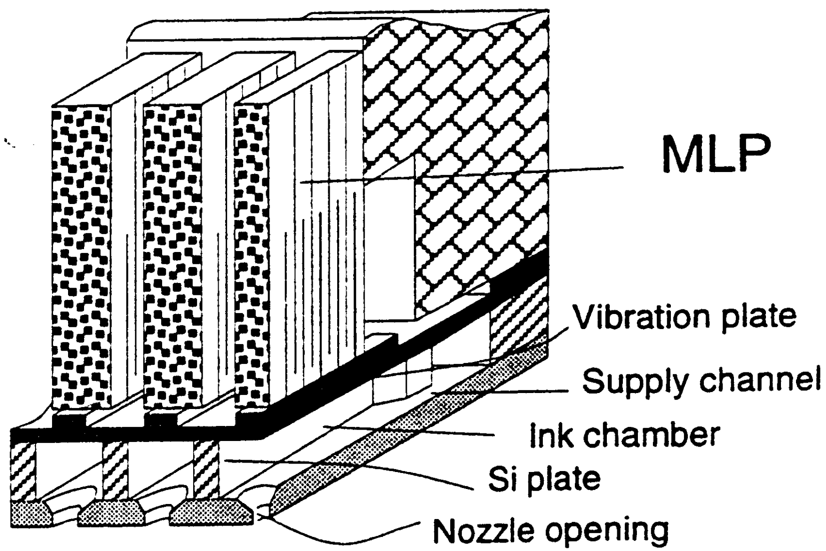
Transversal actuator action of a PXE 5 plate

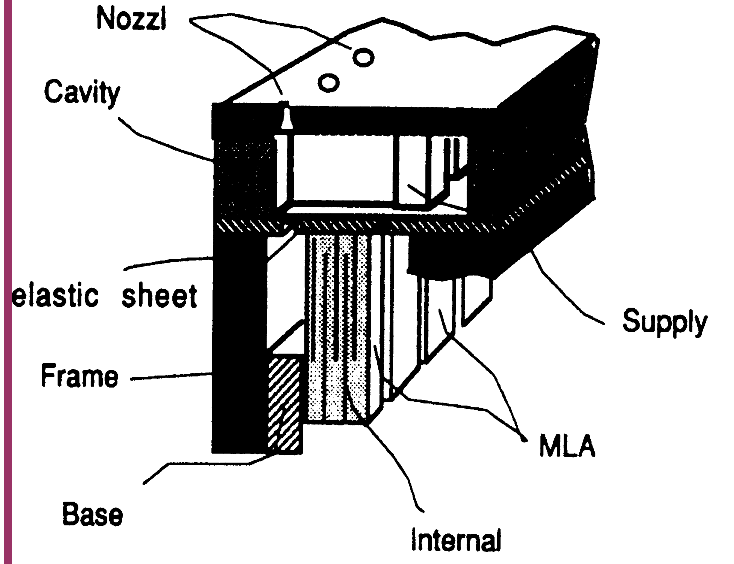
Strain $(S) = \delta L / L = d_{31} \times E$

$\delta L = L \times d_{31} \times E = L/h \times d_{31} \times V$

Piezo Printheads

- Three Types:
  – Rod type.

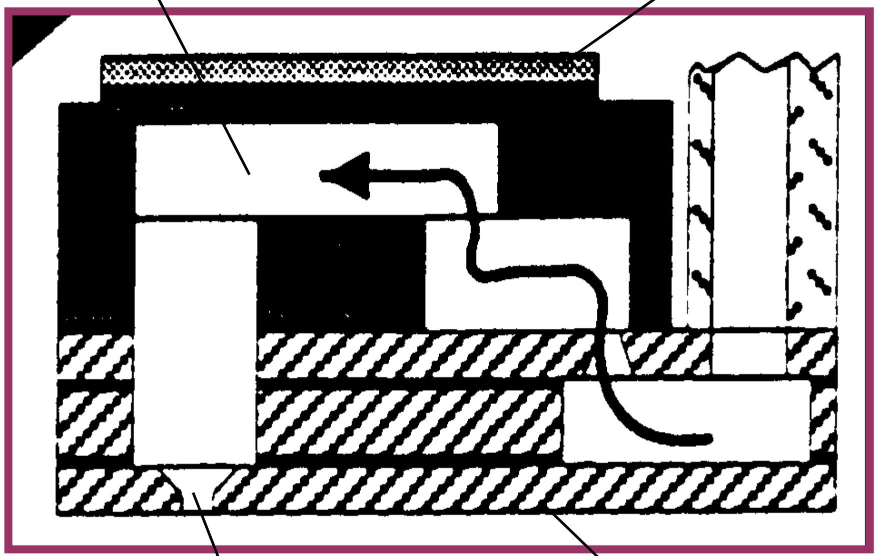


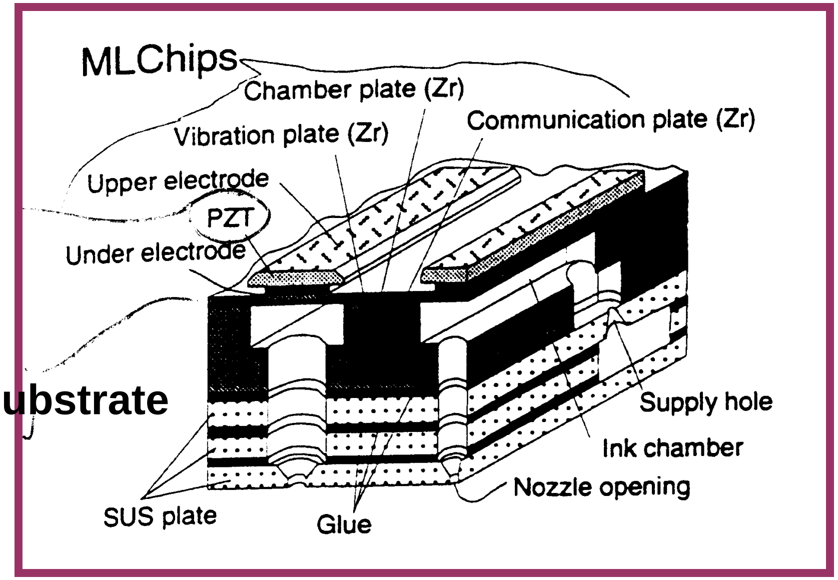


Using multilayer piezoelectric (PZT) ceramic actuator arrays

Piezo Printheads

– Chip type

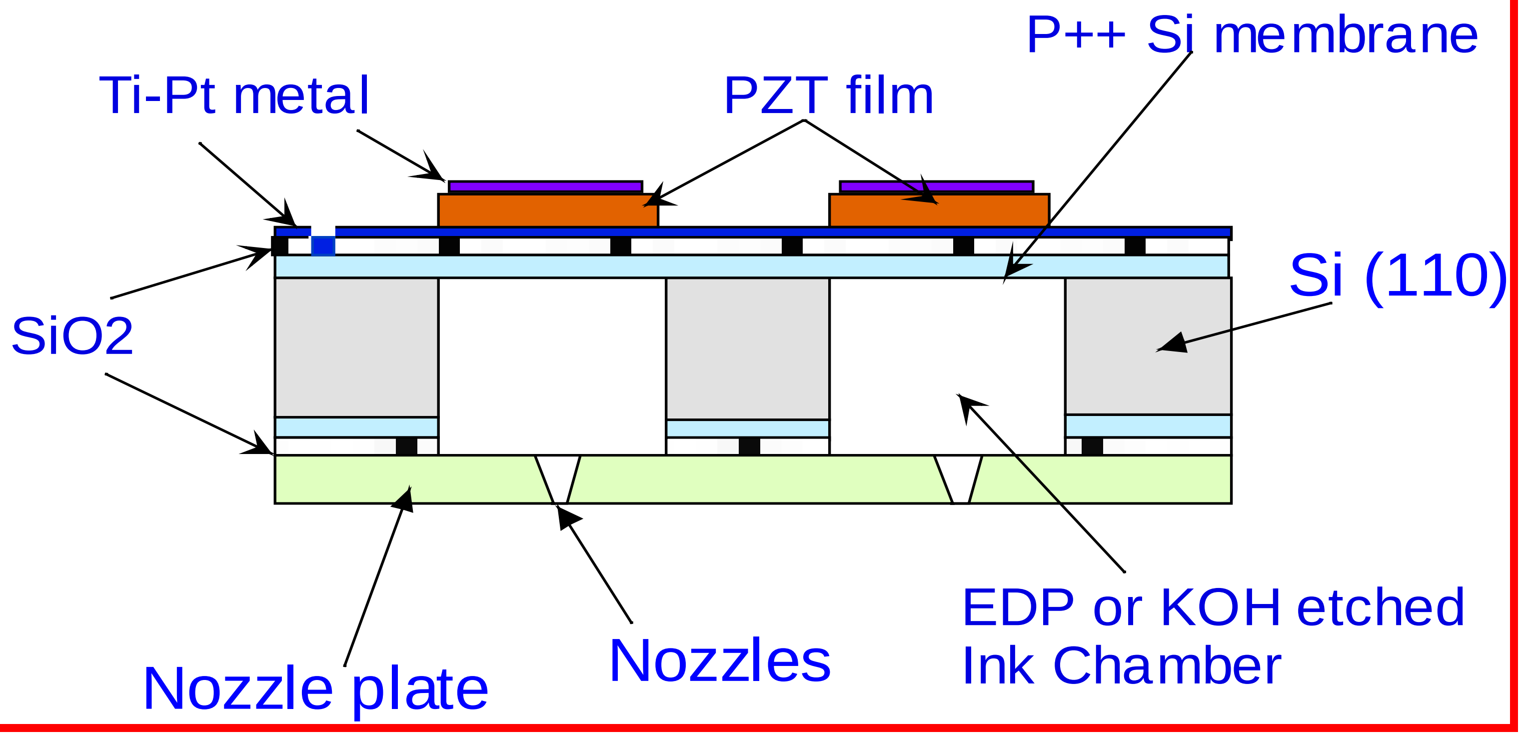




Using bending mode PZT ceramic actuators arrays

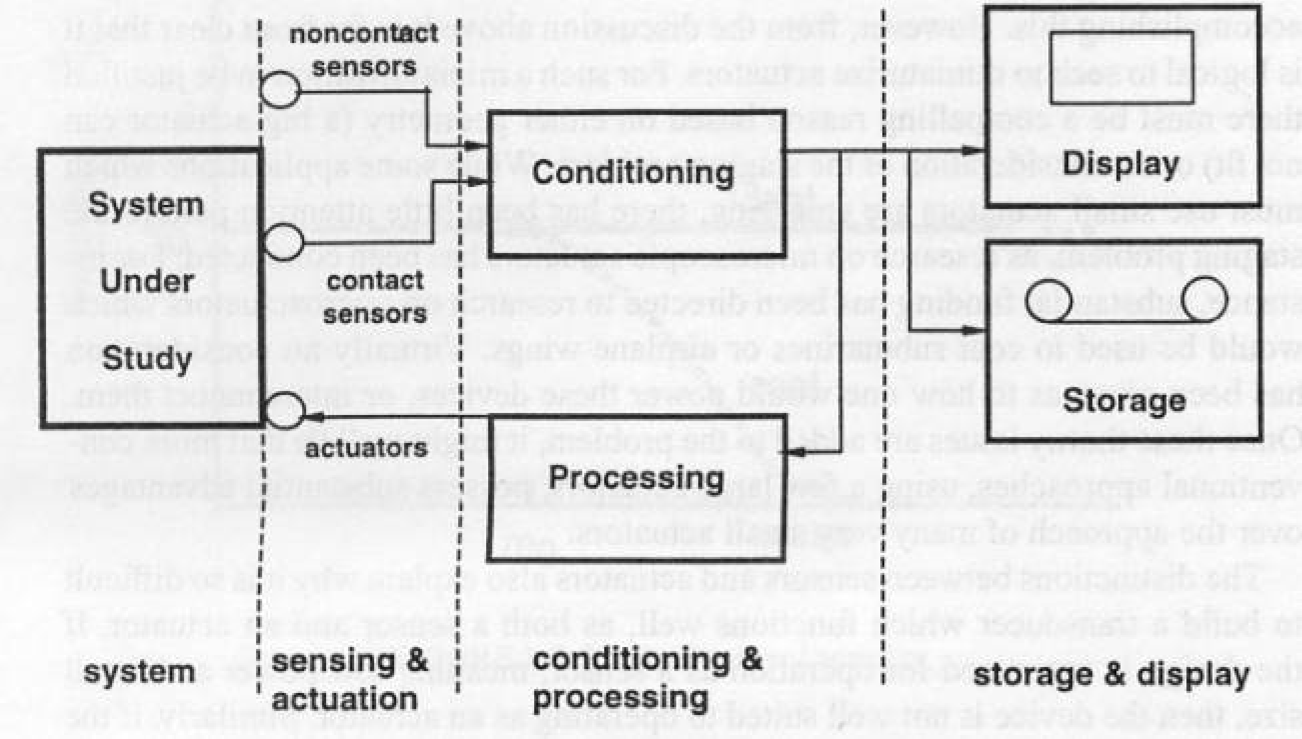
d31 Bending Actuators

Cross-Section of Ink Jet Piezo-actuators



Sensors and Actuators

- **Transducers as part of a measurement or control system**



Categories of sensors and actuators

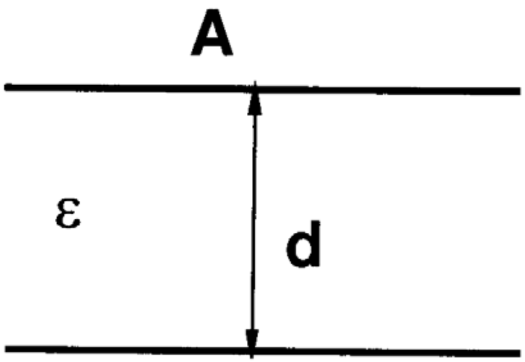
Transducers have been classed in three ways

- Categorized by their use
  - Microphone, accelerometer, force sensor, displacement sensor, gas sensor, humidity sensor, temperature sensor, etc.
  - This is the most common classification scheme found in books on measurement or on sensors
  - Not good for a fundamental understanding of the transduction processes because physical principles may be quite similar in devices with very different applications

Example: Consider a sensor based on parallel plate capacitor

$$C = \frac{\varepsilon A}{d}$$

- ε is the dielectric permittivity
- A is cross section area of the plate
- d is the separation
- C is capacitance



Categories of sensors and actuators

- Sensors can be designed by allowing any one of three parameters to vary in manner which provides a one-one correspondence between the parameter values and the desired quantity to be measured (the measurand)
  - A humidity sensor, which exploits a variation in permittivity ε. It uses a material in which ε is a function of moisture content
  - A position sensor, which exploits a variation in the effective area A in which one capacitor plate is fixed while the other moves laterally
  - A condenser microphone: one of the plate move in response to sound pressure, thus changing the gap d between the plates

  They are all based on the same transduction principle: <u>Capacitive Sensor</u>

- Categorized by the energy type their use
  - Capacitive devices rely energy in an electric field
  - Inductive devices rely on magnetic field
  - Resistive devices work through the irreversible conversion of energy

  The categories are so broad as to make comparison of transducers difficult

Sensors and Actuators

- Categorized by material or structural behavior which leads to transduction. This effectively introduces subclass into
  - Capacitive device
  - Inductive devices
  - Resistive devices
  - Piezoelectric devices
  - Pyroelectric devices, etc.

  There are many such subclasses.

  We will use this classification in this course. By using this categories, people can see similarities between various transducers, while understanding the details of the transduction mechanisms associated with each class.

System Analogies

System Analogies

In developing a logical set of analogies between energy domains, we begin with the definition of fundamental variables. There are two sets of fundamental variables which are defined for each energy domain: power conjugate variables and Hamiltonian variables.

Power conjugate variables are two variables which when multiplied yield the power in a given energy domain. This definition permits a large number of choices of variable sets for any given energy domain, but it is traditional to choose those variables most easily measured. For example, in mechanical systems in translation, we could use force and velocity, or time rate of change of force and displacement. The former pair is the standard choice. The standard power conjugate variables are listed below:

- Translational: force, F, and velocity, V.
- Rotational: torque, τ, and angular velocity, Ω.
- Electrical: voltage, e, and current, i.
- Magnetic: magnetomotive force (also called magnetomotance), M, and time rate of change of magnetic flux, $d\phi/dt$.
- Fluid: pressure, P, and volume flow rate, Q.
- Thermal: temperature, T, and time rate of change of entropy, ds/dt.

System Analogies

Firestone or Mobility Analogy

- V, Ω, Q, and e are analogous.
- F, τ, P, and i are analogous.

Using this analogy, the electrical impedance, the ratio of voltage to current, is analogous not to the mechanical and fluid impedances but to the mechanical and fluid mobilities, ratios of velocity to force, and volume flow rate to pressure.

Through-and-Across Analogy

- V, Ω, P, and e are across-variables.
- F, τ, Q, and i are through-variables.

- V, Ω, P and e are referred here as across-variables because they are relative measures typically referenced across an ideal element
- F, τ, Q, and i are called through variables because they are not relative measure and often transmitted through an ideal element
- In this analogy, the electrical and fluid impedances are analogue to the mechanical mobility

System Analogies

Maxwell or Impedance Analogy

- V, Ω, Q, and i are flow variables.
- F, τ, P, and e are effort variables.

In the Maxwell analogy, the electrical, fluid, and mechanical impedances are analogous.

- We can extend this analogy to include thermal and magnetic systems by declaring the magnetomotive force and temperature to be effort variables, and the time rates of changes of magnetic flux and entropy to be flow variables

Expanded Maxwell or Impedance Analogy

- V, Ω, Q, i, $d\phi/dt$, and ds/dt are flow variables.
- F, τ, P, e, M, and T are effort variables.

Maxwell analogy is most frequently used

Lumped element modeling

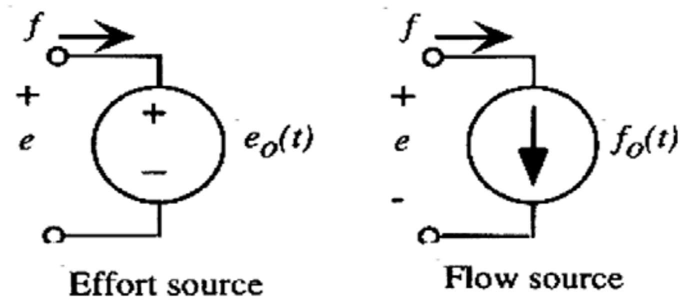
Motivation for Lumped Modeling with Circuit Elements

- Simplified device presentation
- Expressible with equivalent circuit model
  - Can be simulated by SPICE
- Powerful set of tools developed for understanding circuits (at least for EE majors)
- Interface with electronic circuits
  - Modeling of entire system by SPICE

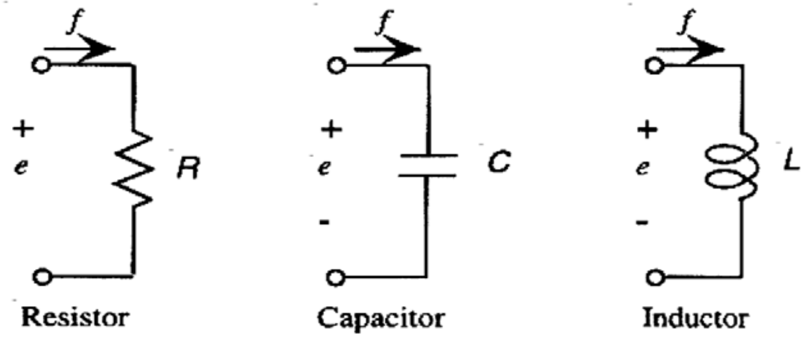
Lumped element modeling

- **One port circuit elements**

Sources

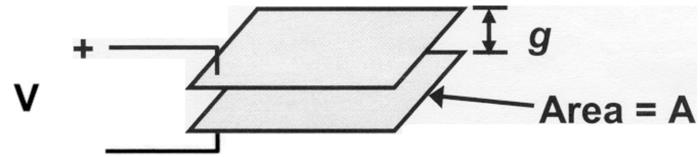


Circuit Elements



Lumped element modeling

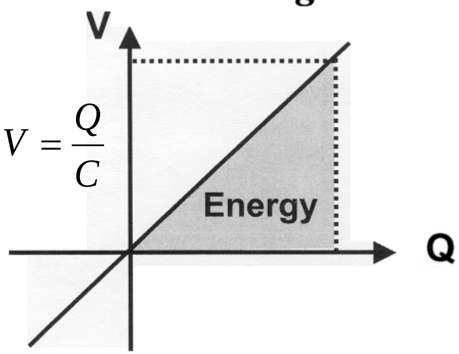
- **Parallel Plate Capacitor**



Linear Capacitor :

$$Q = CV \qquad C = \frac{\varepsilon A}{g}$$

$$V = \frac{Q}{C}$$

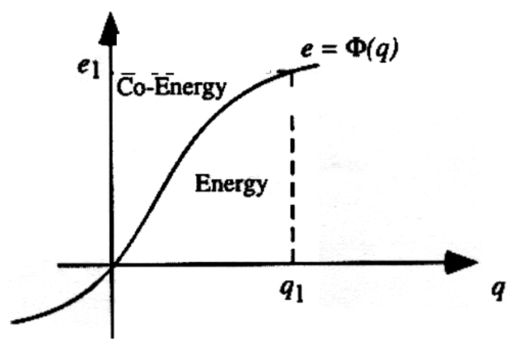


Stored Potential Energy :

$$W(Q) = \frac{Q^2}{2C}$$

Generalized Capacitor:

Well-behaved function that goes through origin of the e-q plane



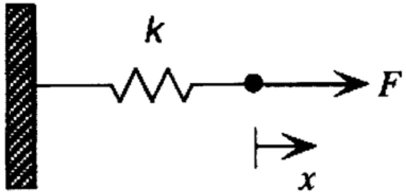
Stored Potential Energy :

$$W(q_1) = \int_0^{q_1} e \cdot dq = \int_0^{q_1} \Phi(q)\,dq$$

Lumped element modeling

- Equivalent circuit of a spring

	Effort	Flow	Momentum	Displacement
Electrical Circuit	V voltage	I current		Q charge
Mechanical System	F force	v velocity	p = mv	x position



$$V = \frac{1}{C}Q$$

$$W(Q) = \frac{1}{2}\left(\frac{1}{C}\right)\cdot Q^2$$

Electrical

$$F = kx$$

$$W(x) = \frac{1}{2}kx^2$$

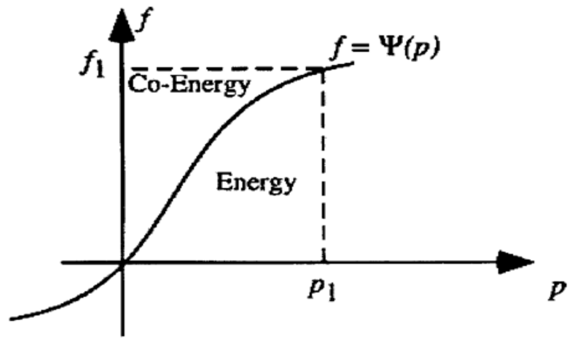
Mechanical

$$\longrightarrow \boxed{C_{spring} = \frac{1}{k}}$$

Equivalent Circuit of a Spring

Lumped element modeling

- **Generalized Inductors**



Stored Kinetic Energy : $W(p_1) = \int_0^{q_1} f \cdot dp = \int_0^{q_1} \Psi(p) dp$

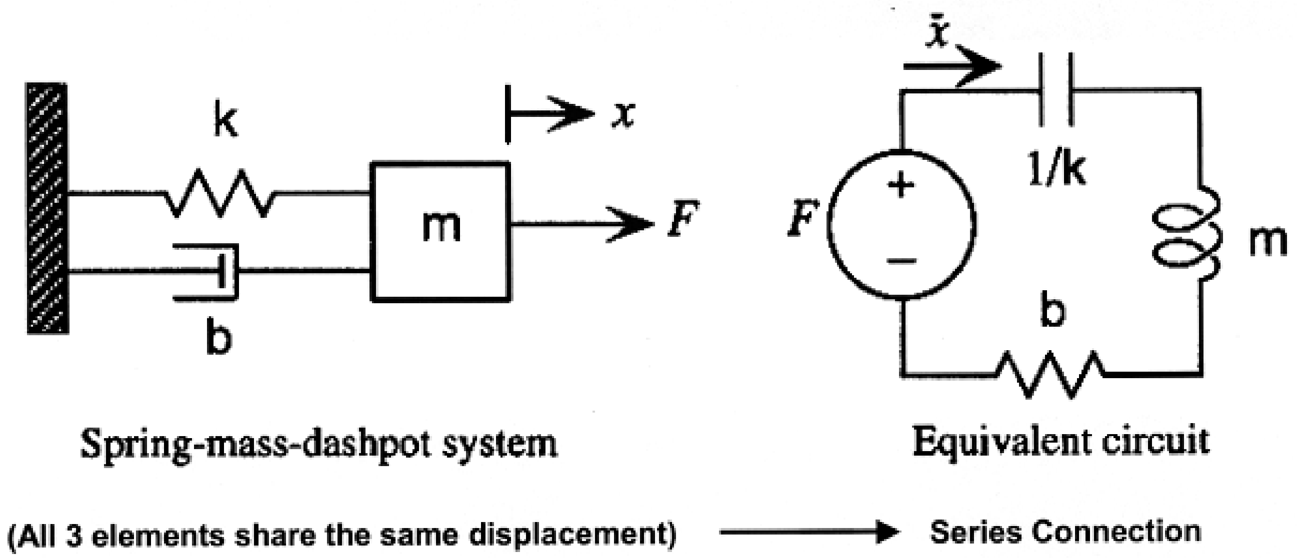
Linear Inductor: $W(Q) = \frac{1}{2} L I^2 = \frac{1}{2} L \left(\frac{dQ}{dt} \right)^2$

Inertia Mass: $W(p) = \frac{1}{2} m v^2 = \frac{1}{2} m \left(\frac{dx}{dt} \right)^2$

Equivalent Circuit of a Spring: $\boxed{L_{spring} = m}$

Lumped element modeling

- **Equivalent circuit for spring-mass-dashpot system,**



Connection rule for the equivalent circuit for e⌫V convention:

• Elements share a common flow or displacement ⌫ connected in Series

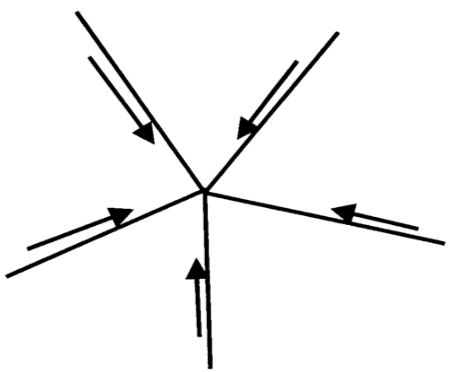
• Element share a common effort ⌫ connected in Parallel

Lumped element modeling

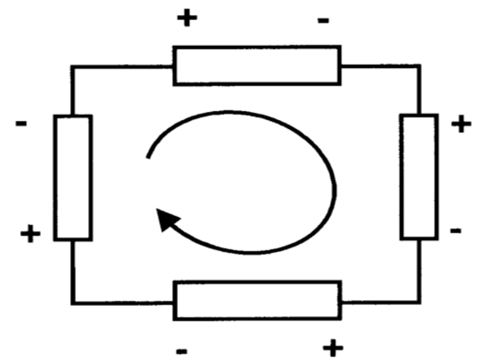
- **Kirchhoff's Laws**

  Kirchhoff's Current Law (KCL)
  - The sum of all currents (flow) entering a node is zero

  Kirchhoff's Voltage Law (KVL)
  - The oriented sum of all voltages (efforts) around any closed loop is zero



KCL

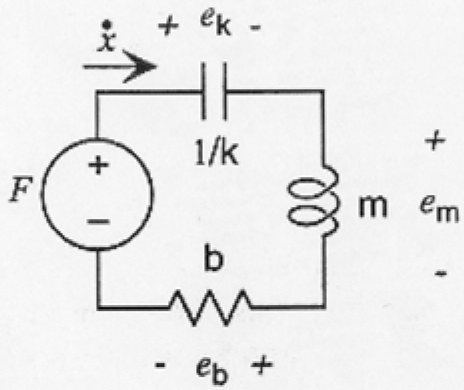


KVL

Lumped element modeling

- **Dynamic Response from Equivalent circuit**

KVL: $-F + e_k + e_m + e_b = 0$



Dynamic Response → Laplace Transform

$$Z_C(s) = \frac{1}{sC}$$

$$Z_L(s) = sL$$

$$Z_b(s) = b$$

$s = j\omega$

$$e(s) = Z(s)f(s) = \left(sL + b + \frac{1}{sC}\right)f(s)$$

Electrical-to-Mechanical Mapping

$$L \rightarrow m$$

$$b \rightarrow b$$

$$\frac{1}{C} \rightarrow k$$

$$e(s) \rightarrow F(s)$$

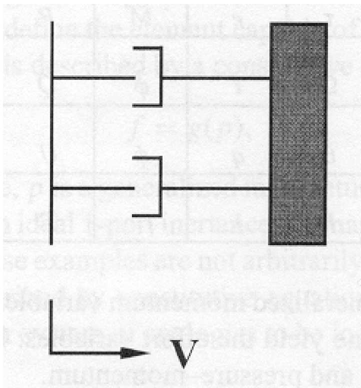
$$f(s) \rightarrow \dot{x}(s)$$

$$\frac{\dot{x}(s)}{F(s)} = \frac{1}{sm + b + k/s} = \frac{s}{s^2 m + sb + k}$$

Second-order system

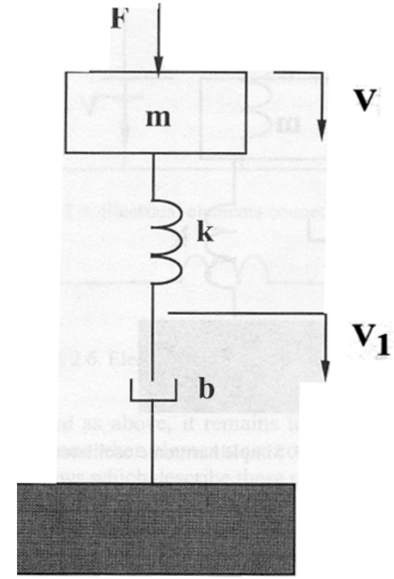
Lumped element modeling

- **Equivalent circuit of mechanical systems**



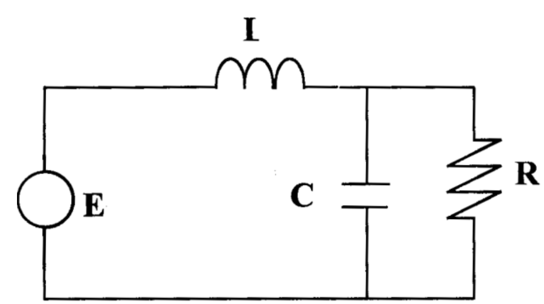
Two dampers mechanically in parallel.

Simple mechanical system.



Two resistors electrically in series.

Equivalent circuit



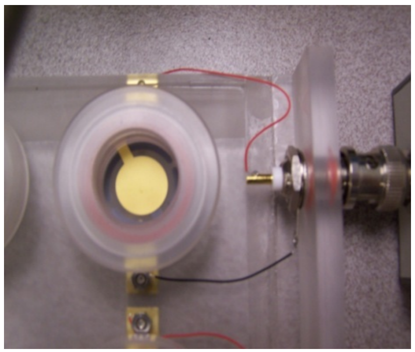
Example 4

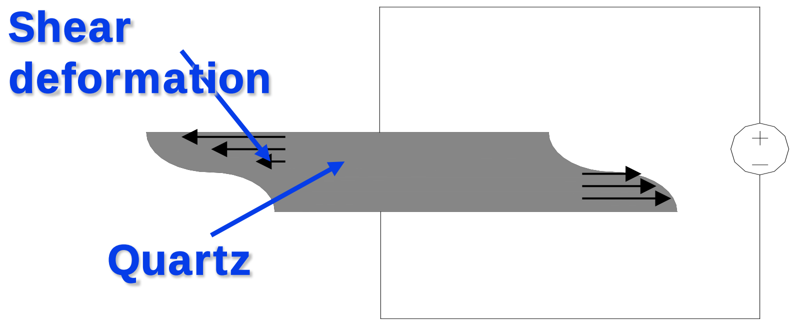
Thickness Shear Mode (TSM)

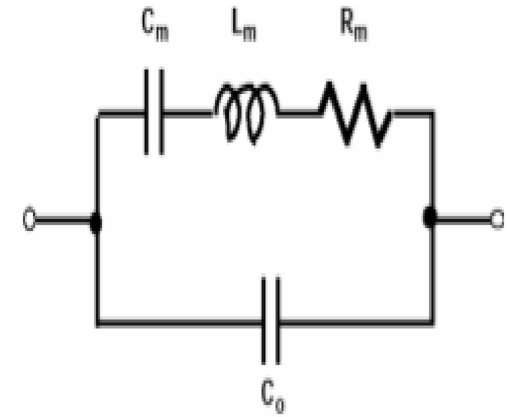
Bulk Acoustic Wave (BAW) Resonator Sensor

Equivalent Circuit of TSM Sensor

- Near resonant frequency







- If the applied frequency is exactly equal to resonant frequency, the resonator is a pure resistance in parallel with a static capacitance C_o

$$f_r = \frac{1}{2\pi(LC_1)^{1/2}}$$

Theory of TSM resonator sensor

- The resonant frequency shift is linearly related to the mass changes

for the rigid layer in gas phase →

$$\Delta f = -\frac{2 f_0^{\,2}}{(\rho_Q \mu_Q)^{1/2}} \times \frac{\Delta m}{A}$$

-Sauerbrey 1959

- The effects of the solution viscosity and density on the resonant frequency of TSM sensor are

viscosity is not high and one side of TSM sensor is contacted with the solution →

$$\Delta f = -\frac{f_0^{\,3/2} (\rho_L \eta_L)^{1/2}}{(\pi \rho_Q \mu_Q)^{1/2}}$$

- ρ_L- density of liquids
- η_L- viscosity of liquids

-Kanasawa et al. 1985