Microssistemas

Estudo de casos

PIEZORESISTIVE PRESSURE SENSOR

Piezoresistivity

- Piezoresistivity is the dependence of electrical resistivity on strain.
- The resistivity of a material depends on the internal atom positions and their motions.

Longitudinal and Transverse Piezoresistance

- If a relatively long, relatively narrow resistor is defined in a planar structure,for example, by ion implantation followed by diffusion,
- then the primary current density and electric field are both along the long axis of the resistor.
- This axis need not coincide with the cubic crystal axes.
- It is necessary to know how to transform the piezoresistive equations to an arbitrary coordinate system.

Piezoresistive Coefficients of Silicon

- The piezoresistive coefficients have been measured for many materials.
- The primary interest in MEMS are the coefficients for silicon.
- These coefficients depend strongly on the doping type, a reflection of the fact that the detailedvalence-band and conduction-band structures in silicon are very different.

Piezoresistive Coefficients of Silicon

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

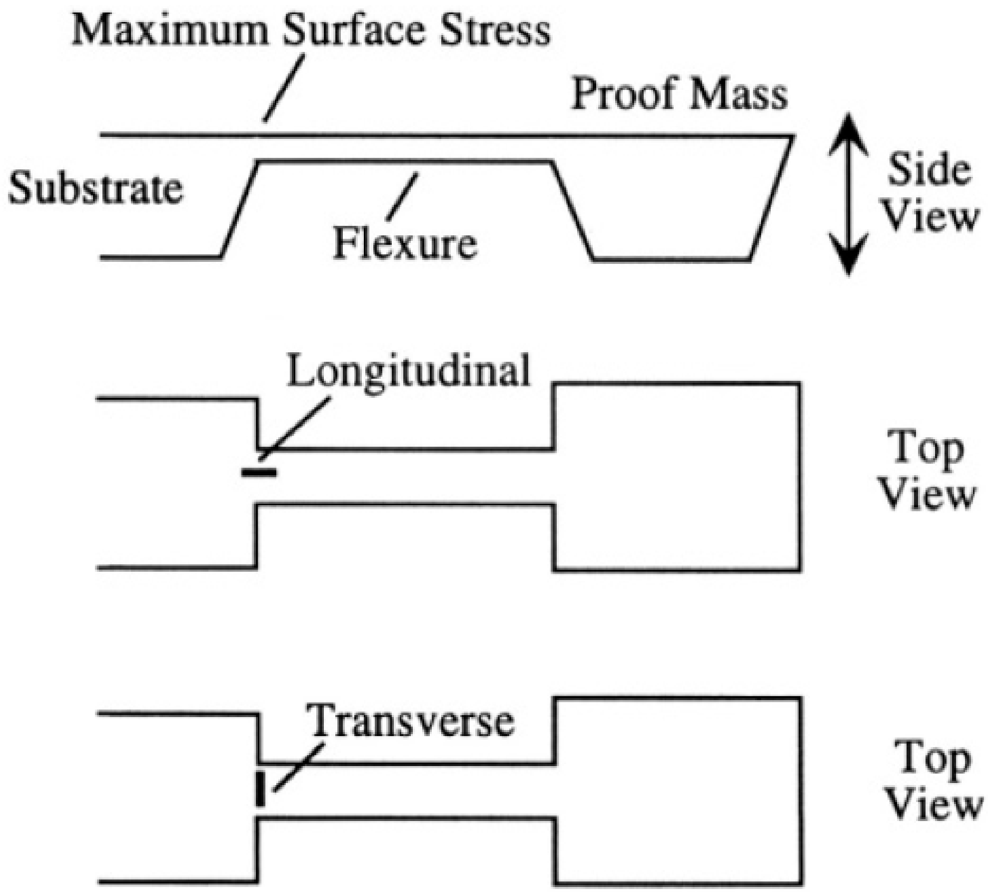
Piezoresistive Coefficients of Silicon

- These coefficients are weak functions of doping level for doping below about but then decrease markedly at high doping.
- The coefficients decrease with increasing temperature, dropping to about 0.7 of their room-temperature value at 150°C.
- The temperature dependence is some what nonlinear, which aggravates the problem of compensating for the temperature

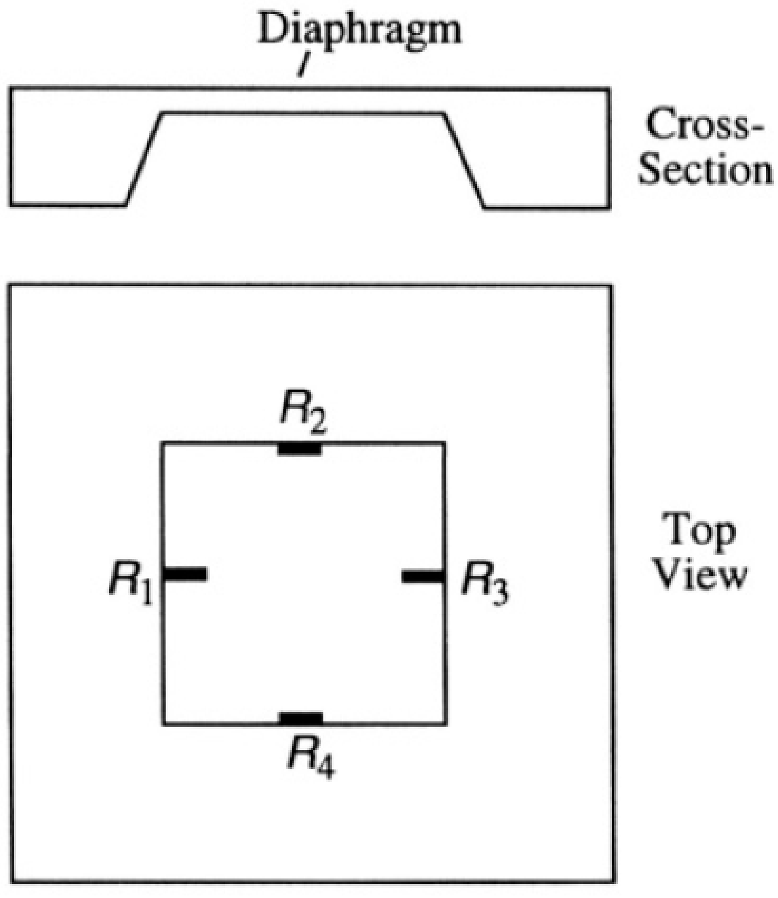
Piezoresistive Coefficients of Silicon

- An important fact is that avthigher doping, the temperature dependence of the piezoresistive coefficients becomes small. Therefore, if it is desired to operate a piezoresistive sensor over a wide temperature range, there may be a design advantage in sacrificing piezoresistive sensitivity in exchange for small temperature dependences by using heavily doped piezoresistors

Two resistor orientations in accelerometer



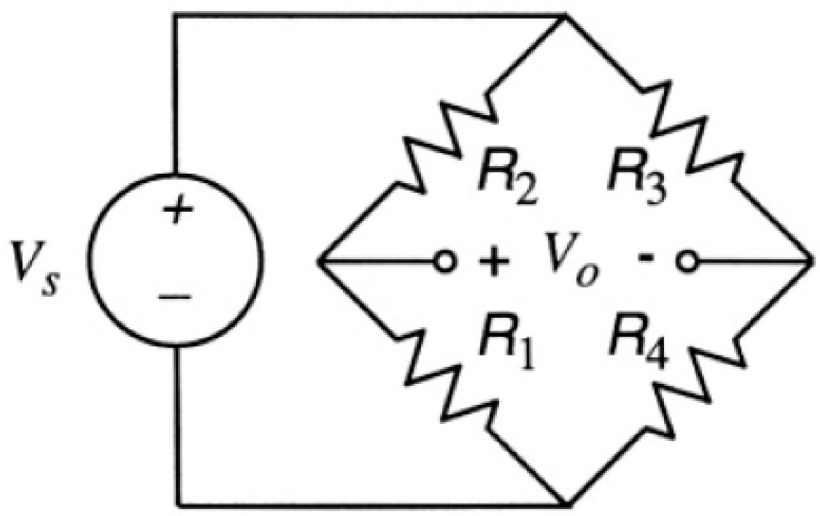
Resistor orientations in pressure sensor



One possible placement of four piezoresistors on a diaphragm pressure sensor. Since this is a bulk micromachined structure, all resistor axes are along one of the <110> directions, and are aligned along an axis of principal stress at the edge of the plate.

Resistor orientations in pressure sensor

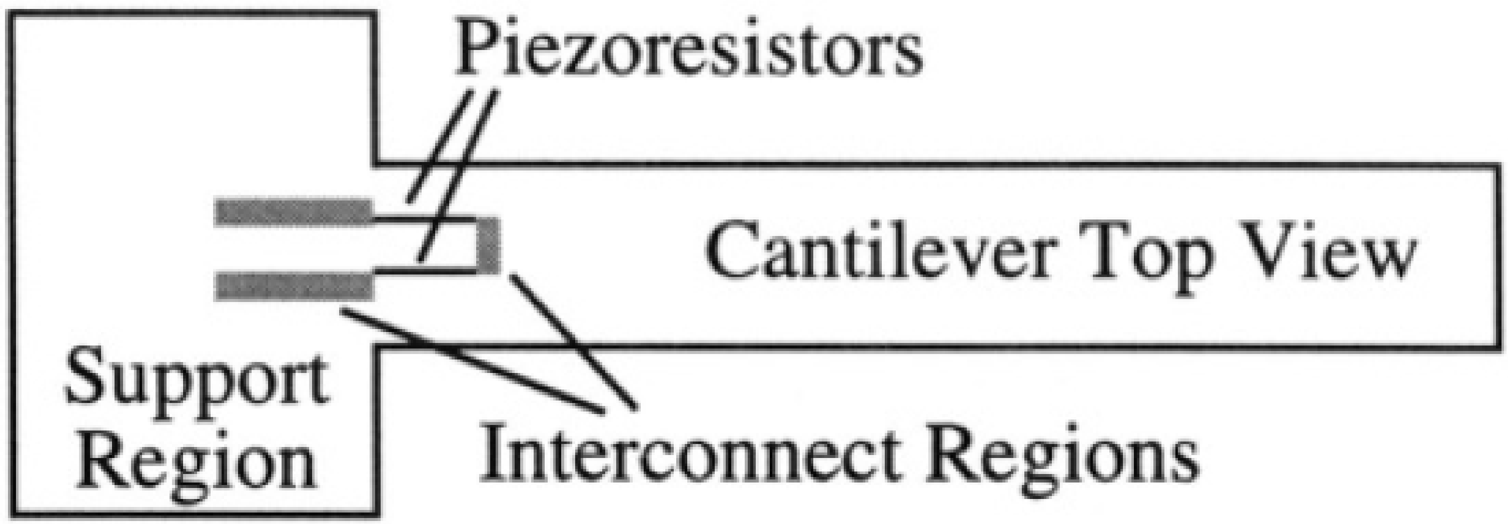
$$R_1 = R_3 = (1 + \alpha_1)R0$$



$$R_2 = R_4 = (1 - \alpha_2)R0$$

$$\frac{V_o}{V_s} = \frac{R_1\,R_3 - R_2 R_4}{(R_1 + R_2)(R_3 + R_4)} \approx \frac{\alpha_1 + \alpha_2}{2(1 + \alpha_1 - \alpha_2)}$$

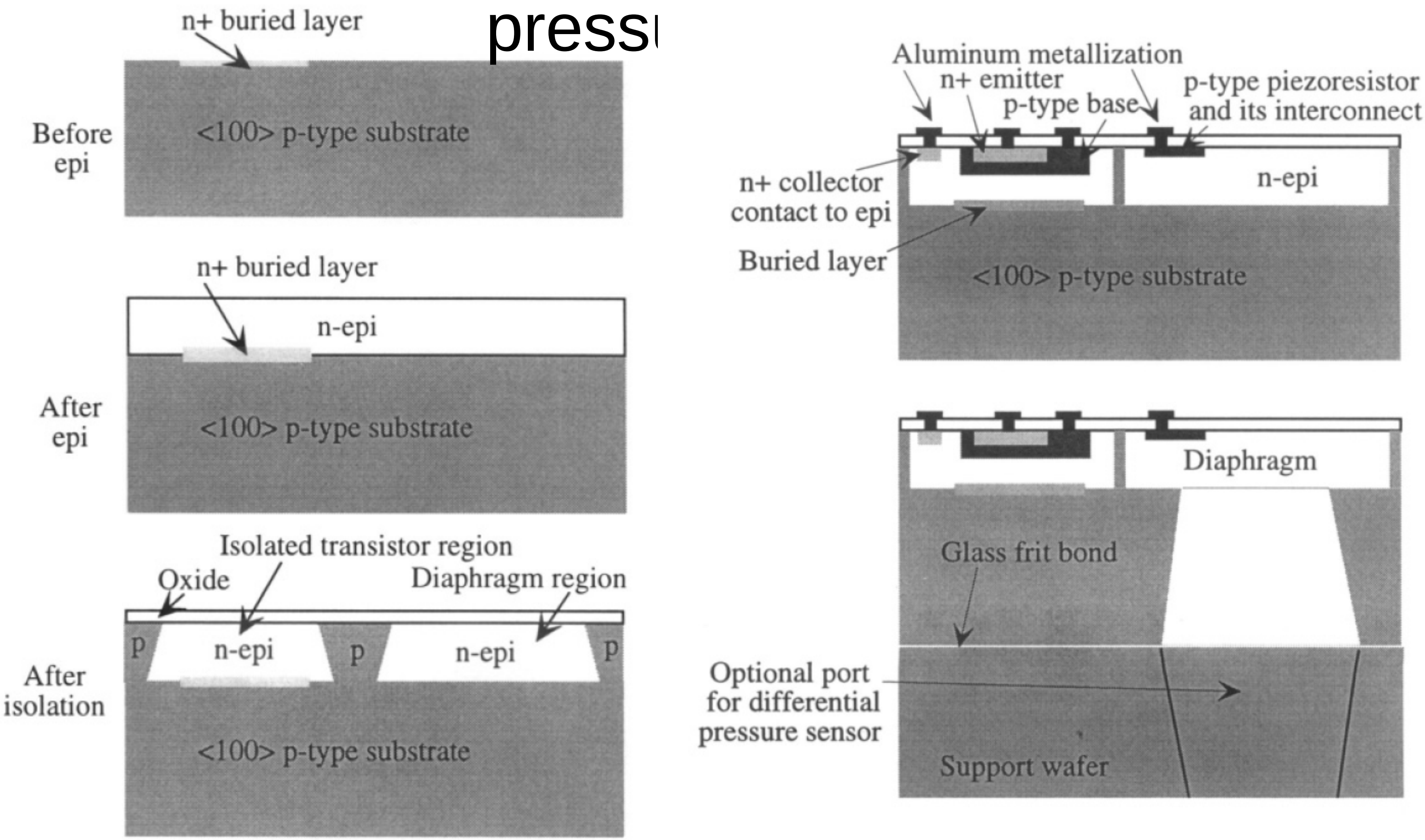
An example using piezoresistance to measure the deflection of a cantilever.



The Motorola MAP Sensor

- The Motorola manifold-absolute-pressure (MAP) sensor uses piezoresistance to measure diaphragm bending and integrates the signal-conditioning and calibration circuitry onto the same chip as the diaphragm. In the discussion to follow, we examine a simplified view of the process flow, the specific piezoresistor configuration used, and details of the associated circuitry and trim procedures, and we discuss the impact of several recent improvements.

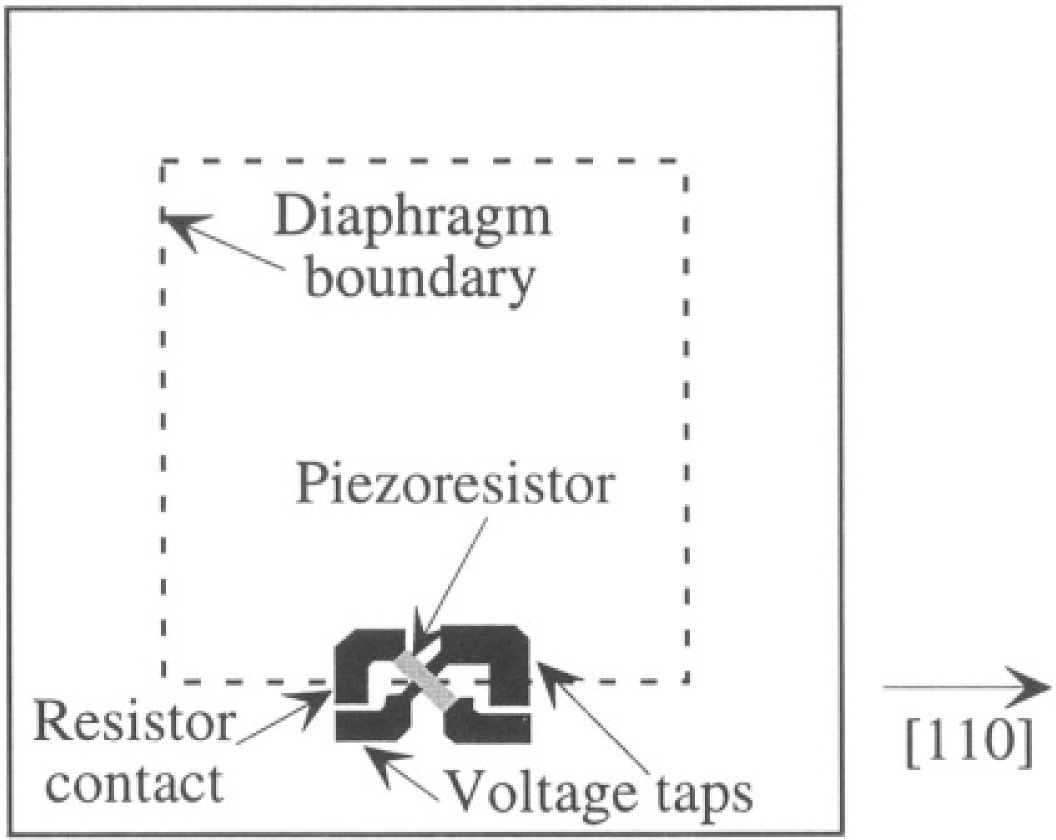
Basic bipolar process adapted for an integrated pressu



Characteristics of membrane

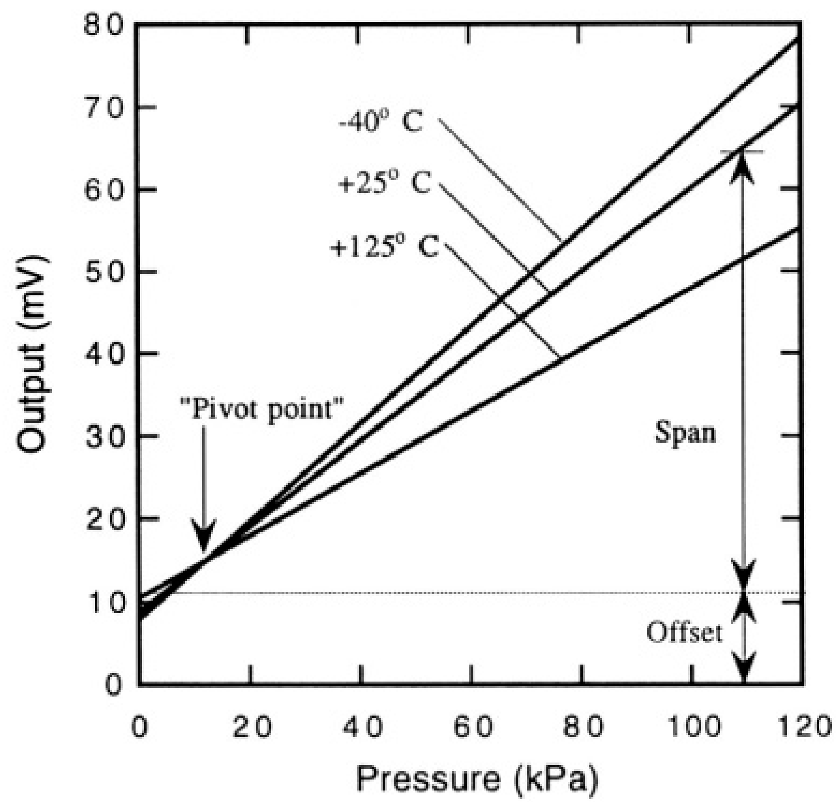
- Typical diaphragm dimensions are 1000 × 1000 square, with a thickness 20 microns.
- The piezoresistor is located near the edge center, where stress is highest.
- The single resistor is oriented at a 45° angle to the side of the square diaphragm,

Characteristics of membrane

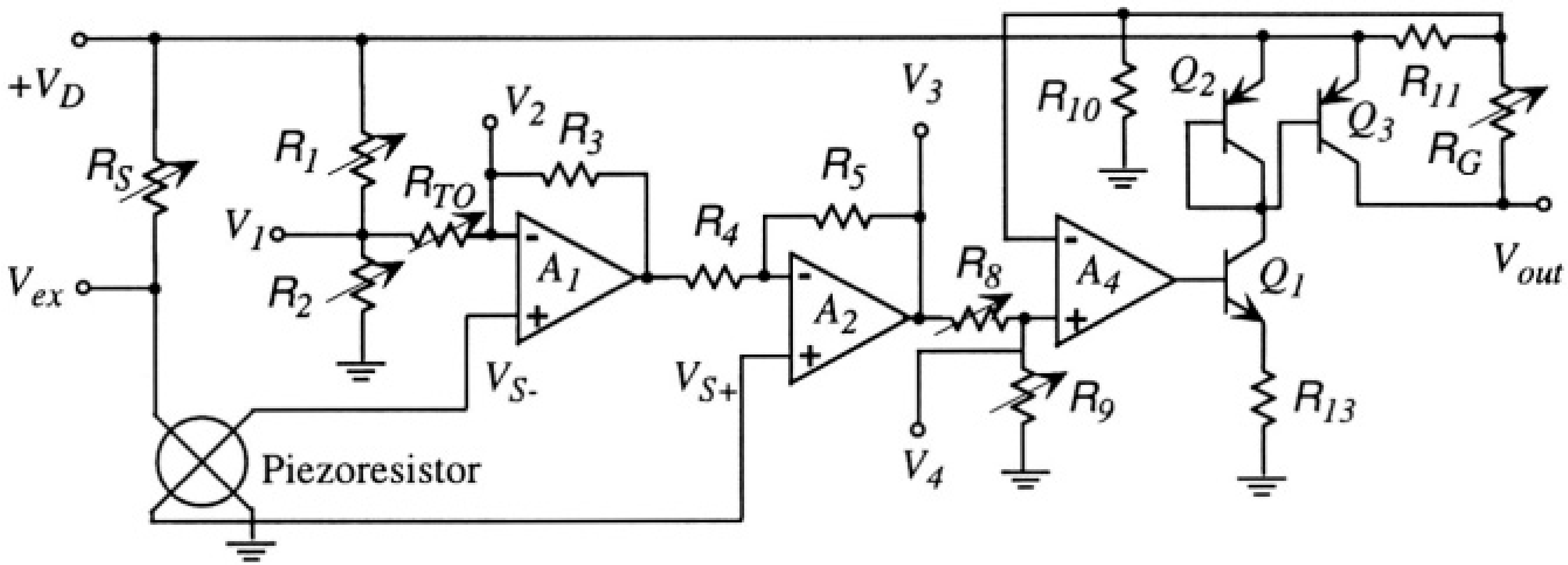


Signal-Conditioning and Calibration

The piezoresistor output requires considerable amplification and modification before a calibrated pressure output is achieved that remains correct over the full operating temperature range of



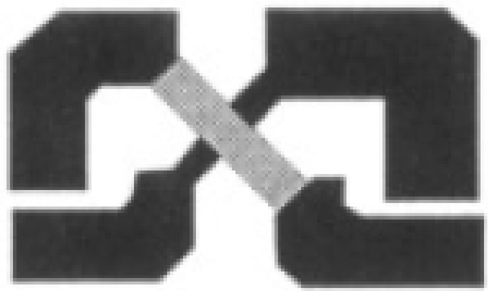
Signal-Conditioning and Calibration



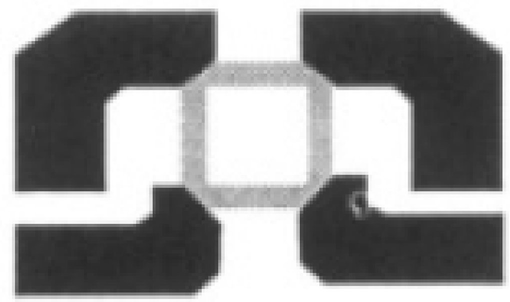
Signal-Conditioning and Calibration

- There are five steps to the calibration: temperature compensation of the span;
- offset adjust, which consists of two trimming steps; temperature compensation of the offset (TCO); and overall gain to set full-scale output.
- Each step requires the laser trimming of one resistor. However, because the target goal can be missed to either side, two of the steps require the presence of two trimmable resistors, one of which is trimmed if the target is missed on the high side, the other if missed on the low side.
- Thus there are seven trimmable resistors in the circuit.
- In order to be able to access each of these resistors during trim and calibration, a total of five test points are added to the three terminals needed to operate the device once the calibration is complete.
- Because the device is placed in its package and wire-bonded prior to calibration, the package must have additional leads for these test points, a maximum of eight leads.

Recent Design Changes



Xducer



Picture Frame

If the diaphragm is made smaller, then it is necessary to improve the dimensional control and placement accuracy of the piezoresistors. Also, if possible, it is desirable to achieve higher sensitivity. Motorola has reported a new “picture frame” piezoresistor design that replaces the Xducer

Higher-Order Effects

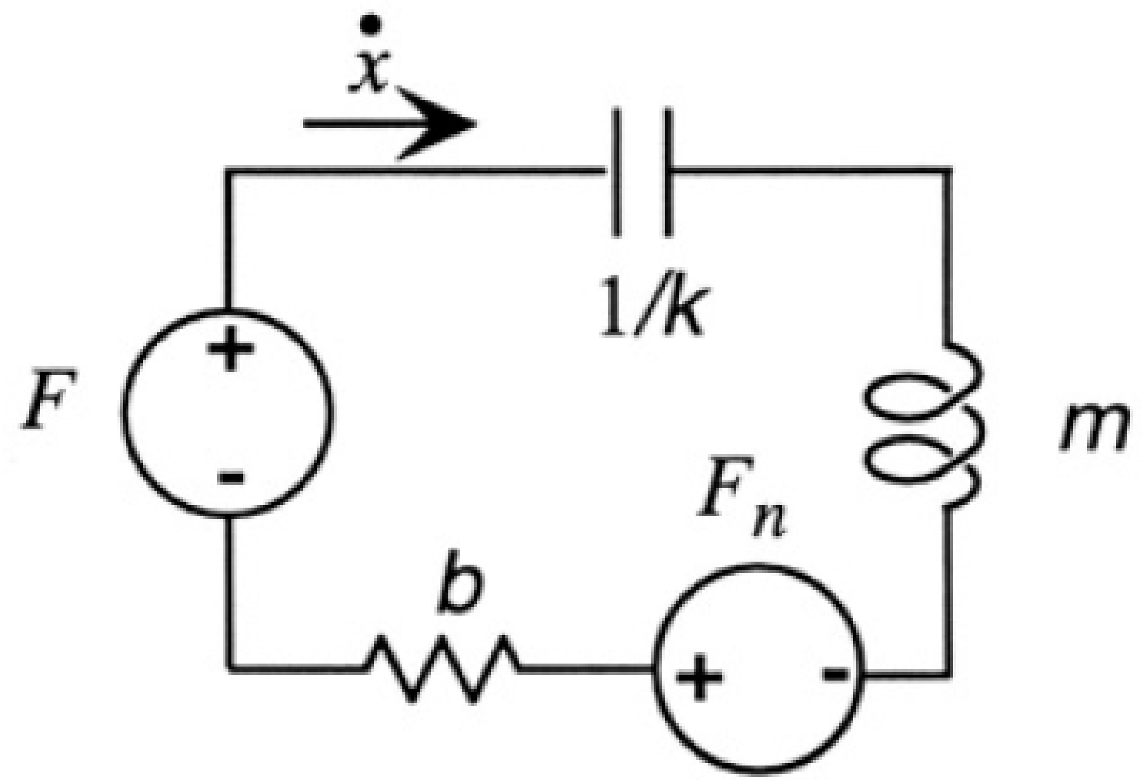
- The preceding discussion has carried us through a first-order calculation of device sensitivity, and a step-by-step calibration procedure. There are, however, many issues that we have stepped around. These include: the longitudinal piezoresistance, which affects the total device resistance; detailed modeling of the stress distribution in the diaphragm, including the effects of the elasticity of the tapered walls at the diaphragm edges; issues of resistor placement and stress averaging, both in the longitudinal and transverse piezoresistivity responses; nonlinearities in the temperature coefficient of resistance over the wide range from -40°C to 125°C; effects of doping variation and lithographic errors on device characteristics.

CAPACITIVE ACCELEROMETER

CAPACITIVE ACCELEROMETER

- The measurement of acceleration, in addition to being a central element of inertial guidance systems, has application to a wide variety of industrial and commercial problems including crash detection for air-bag deployment in cars, vibration analysis of industrial machinery, and provision of feedback signals tosteady the image in a video recorder against hand-held vibration.

Fundamentals of Quasi-Static Accelerometers

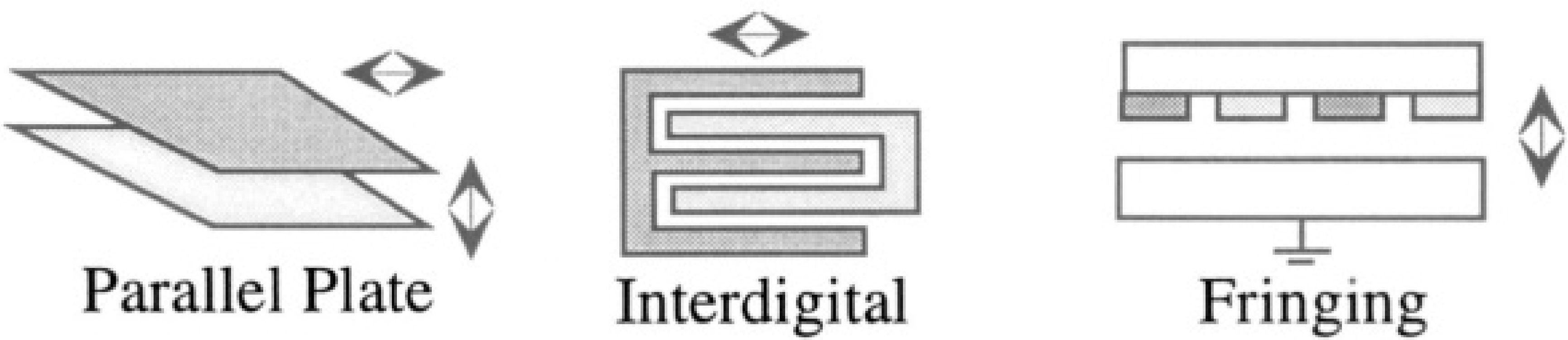


Fundamentals of Quasi-Static Accelerometers

- This a lumped model for a spring-mass-dashpot system with two force sources. *F* represents the external force and Fn represents the equivalent force noise analogous to Johnson noise in a resistor.

Position Measurement With Capacitance

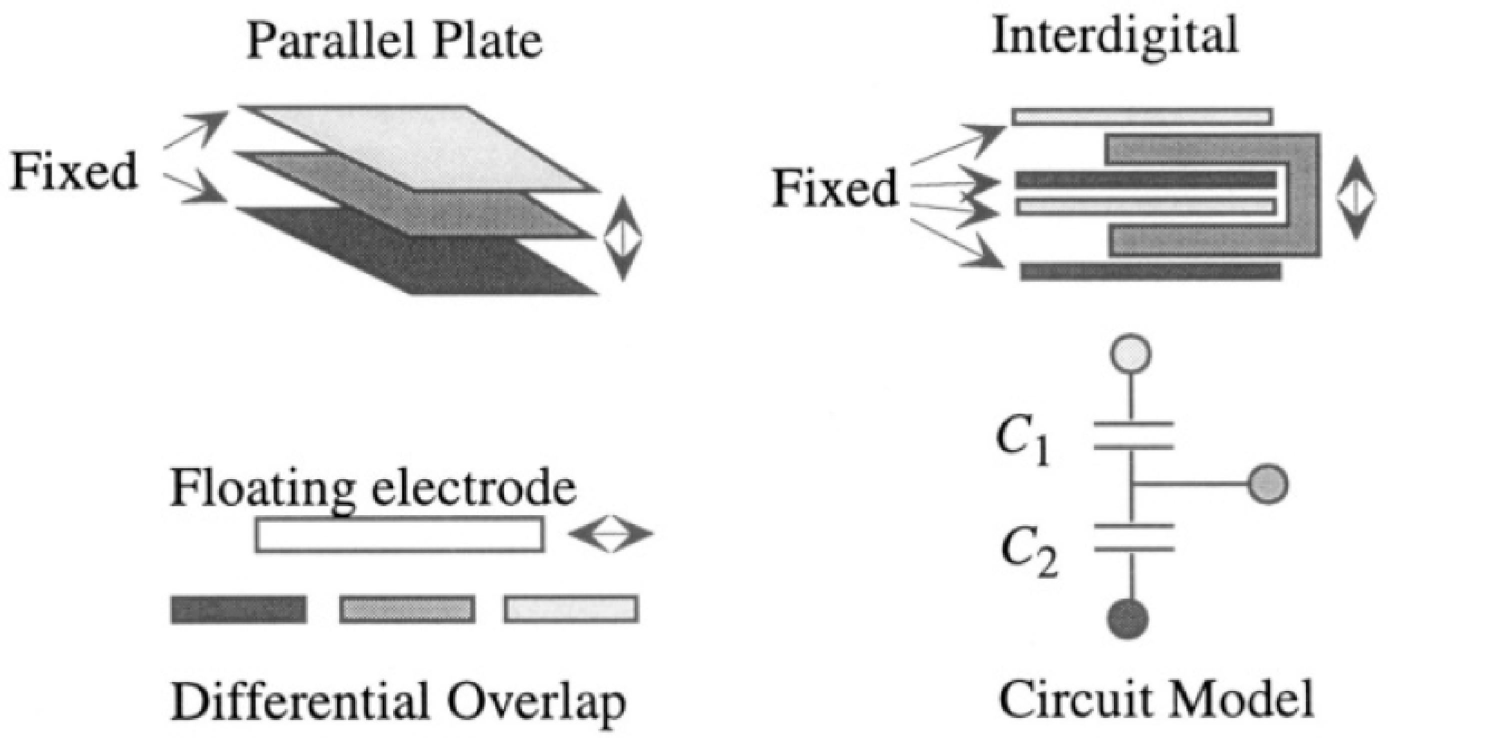
- There are many methods of direct position measurement, for example, capacitance change, inductance change, optical methods, and scanning-probe tips. Of these, capacitance change is the most widely used in microaccelerometers



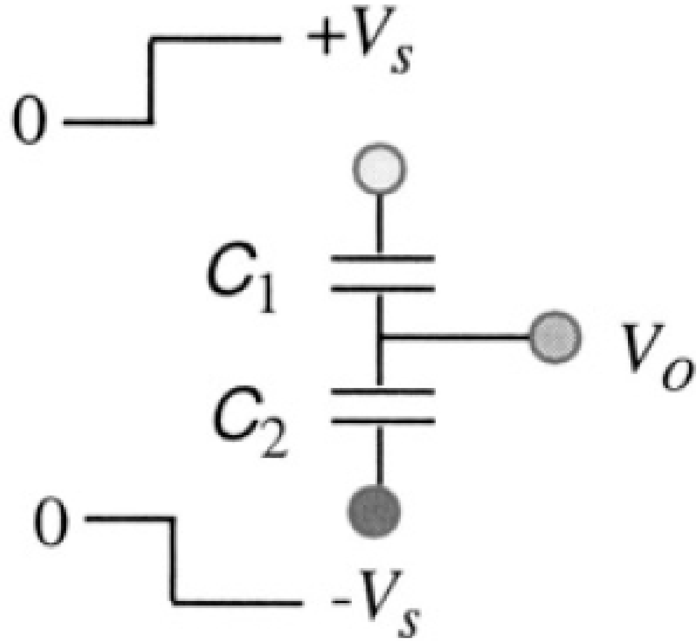
Position Measurement With Capacitance

- The parallel-plate capacitor can vary either with vertical motion of a movable plate, modifying the gap, or by transverse motion of one plate relative to another, modifying the effective area of the capacitor. Interdigital capacitors vary with the degree of engagement of the fingers. Also, displacement of one of the electrodes out of the plane of the figure would modify the capacitance, but this is not a configuration in common use. The fringing capacitance deploys an interdigital set of electrodes on one substrate and detects the change in interdigital capacitance as the electrodes are brought into proximity with a third electrode. If this electrode is grounded, as shown in the figure proximity reduces the interdigital capacitance. If this electrode is floating, proximity increases the interdigital capacitance.

Position Measurement With Capacitance

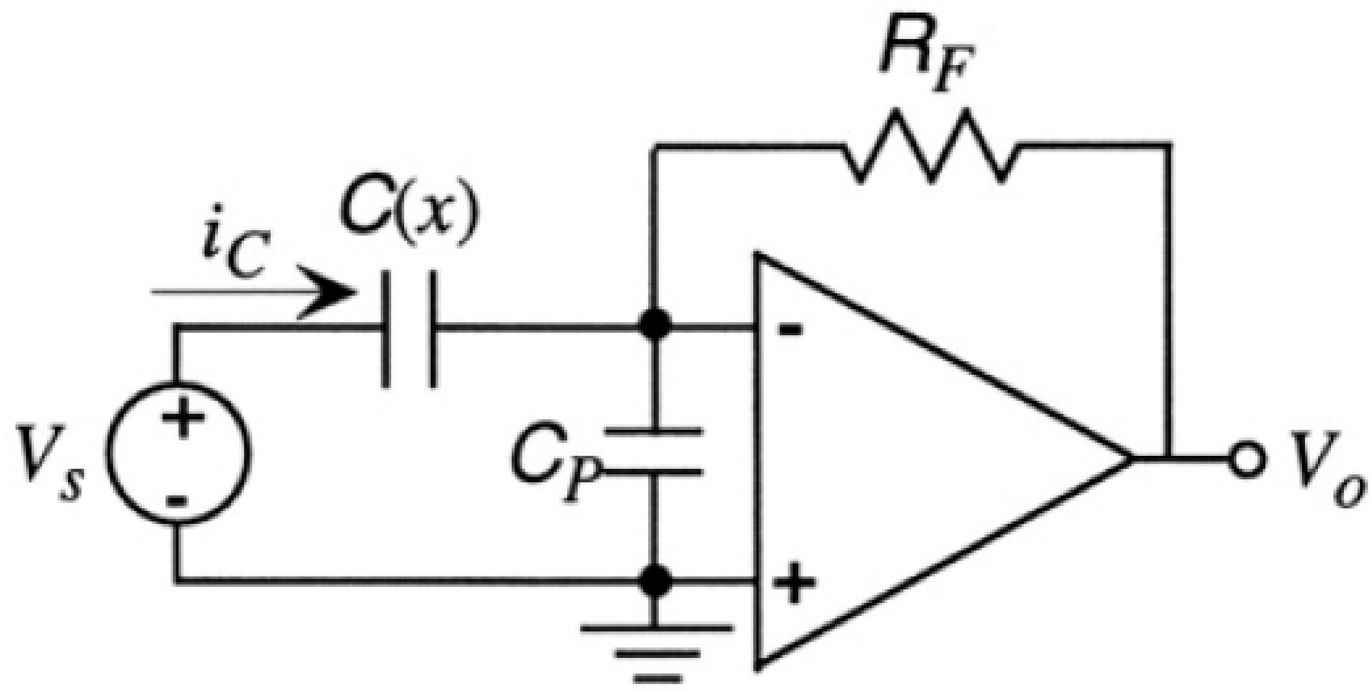


Differential capacitors

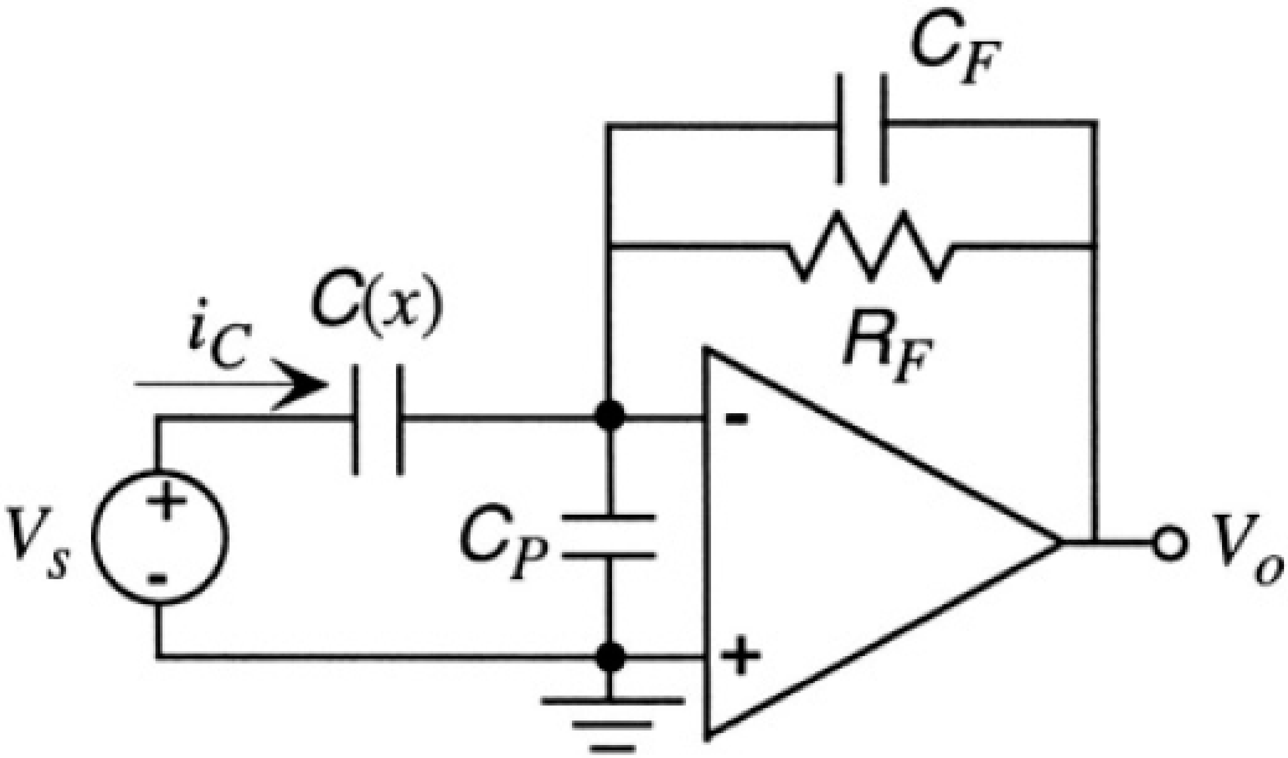


Differential capacitors have the virtue of cancelling many effects to first order, providing a signal that is zero at the balance point and carries a sign that indicates the direction of motion. From a system point of view, a differential capacitor accomplishes linearization about the balance point.

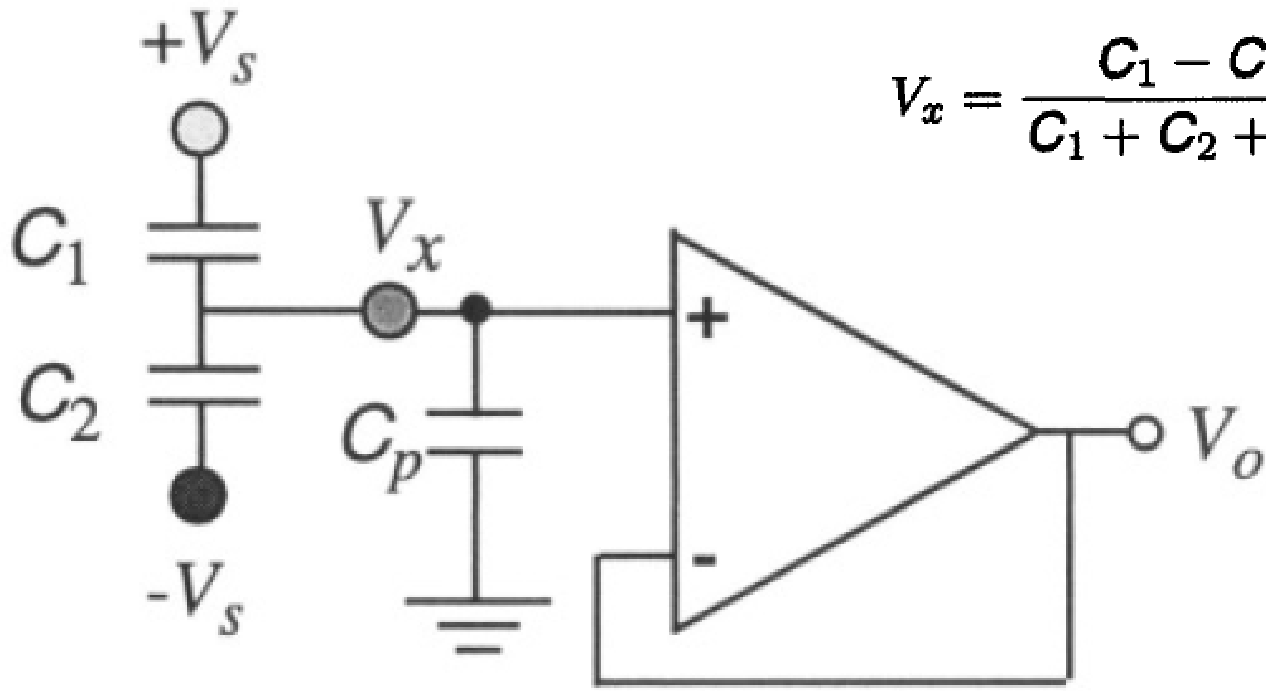
Circuits for Capacitance Measurement



Circuits for Capacitance Measurement



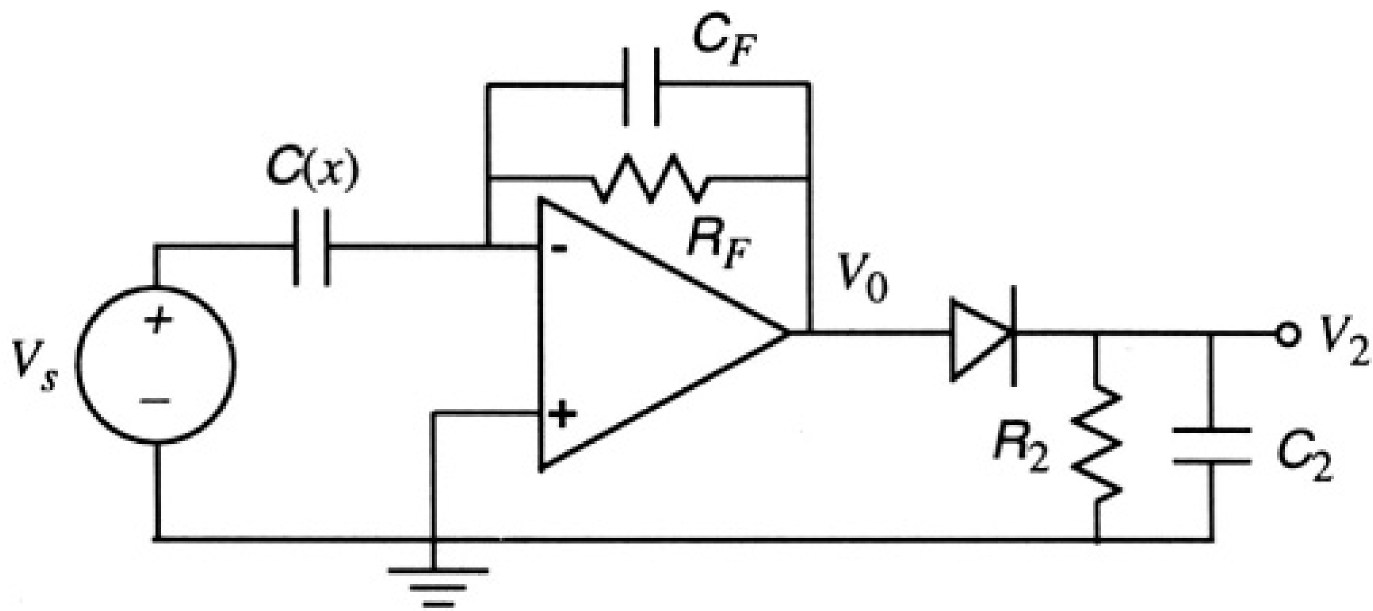
Circuits for Differential Capacitance Measurement



$$V_x = \frac{C_1 - C_2}{C_1 + C_2 + C_P} V_s$$

Circuits for Differential Capacitance Measurement

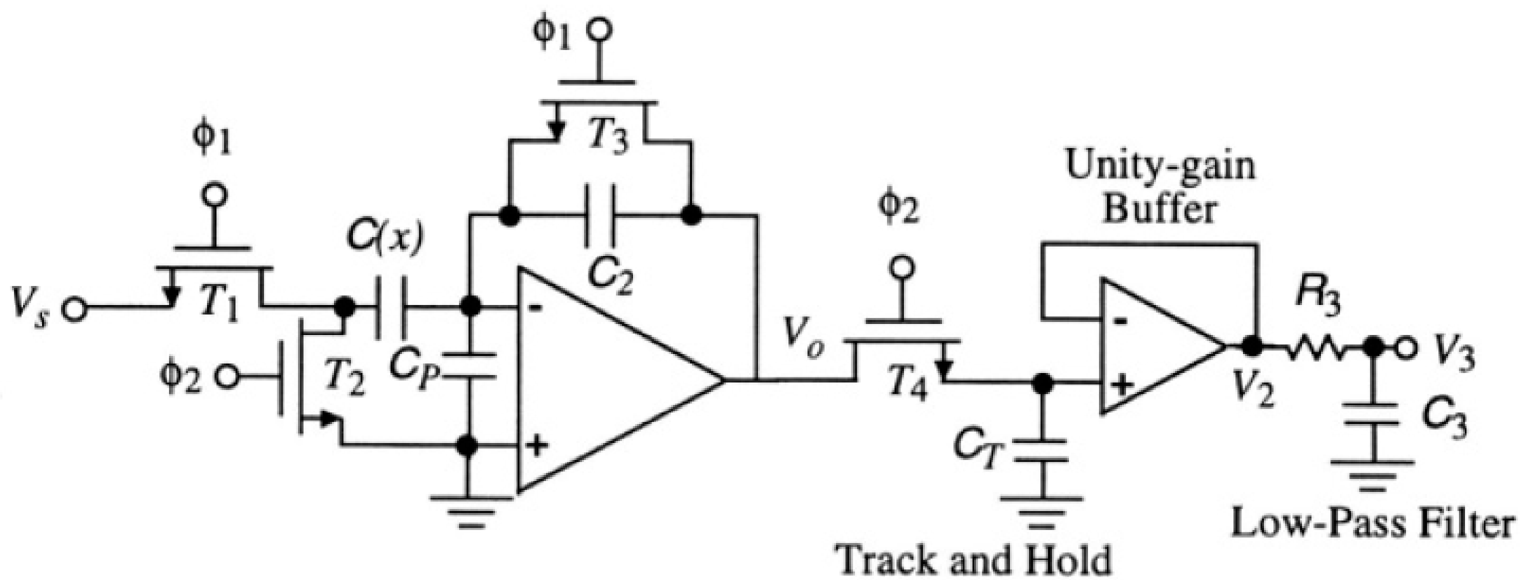
- **Demodulation Methods**



Use of a peak detector to demodulate the capacitance signal

Circuits for Capacitance Measurement

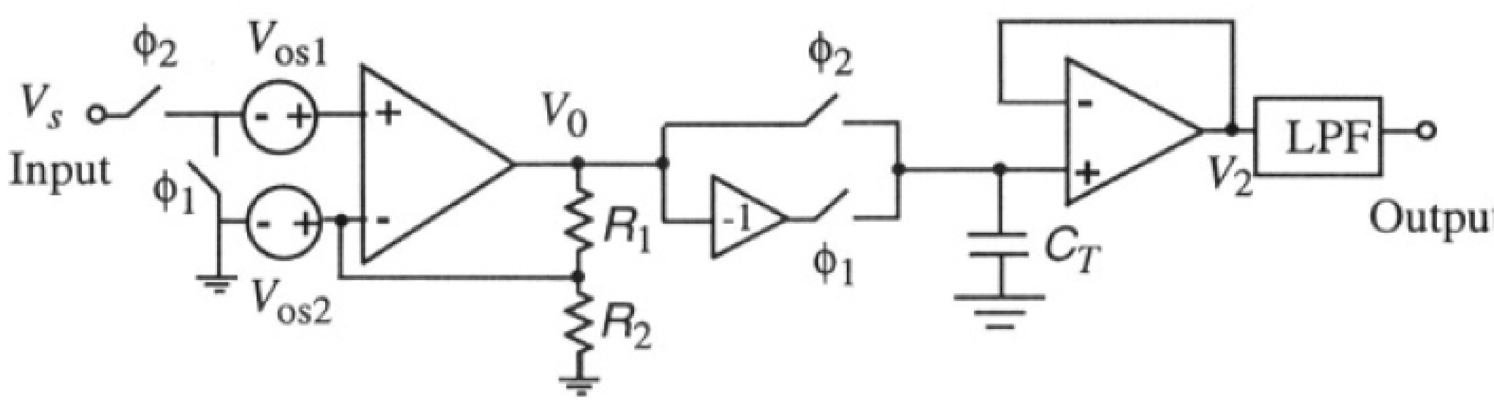
- **Demodulation Methods and Filters**



Use of a peak detector to demodulate the capacitance signal

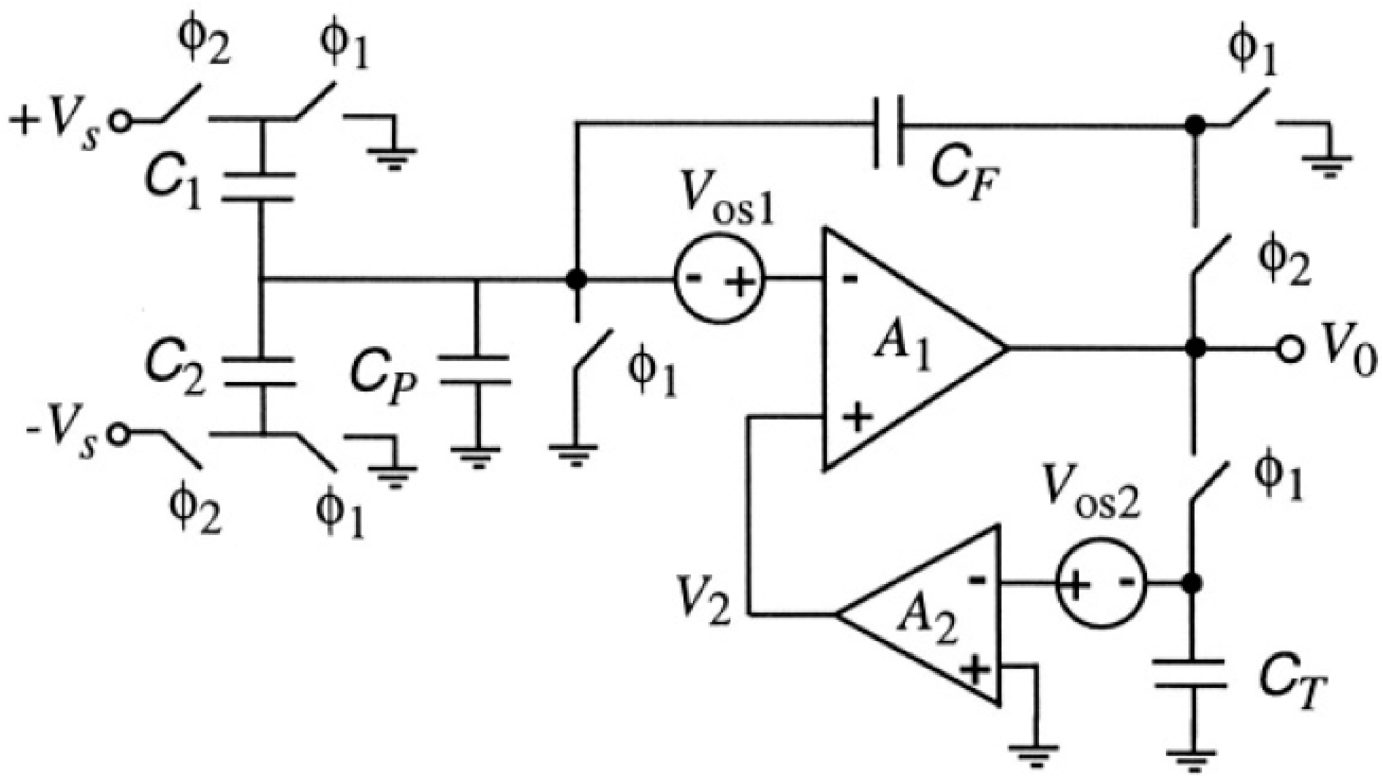
Circuits for Capacitance Measurement

- A *chopper-stabilized* op-amp uses transistor switches to alternate the input of a non-inverting amplifier between the input signal and ground.



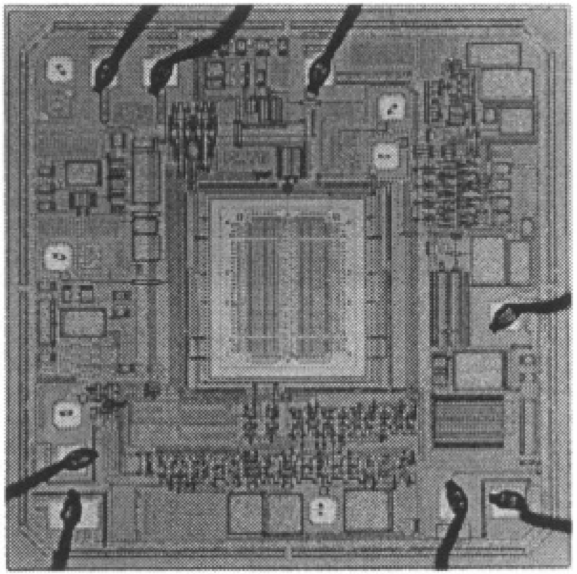
Circuits for Capacitance Measurement

- Correlated Double Sampling

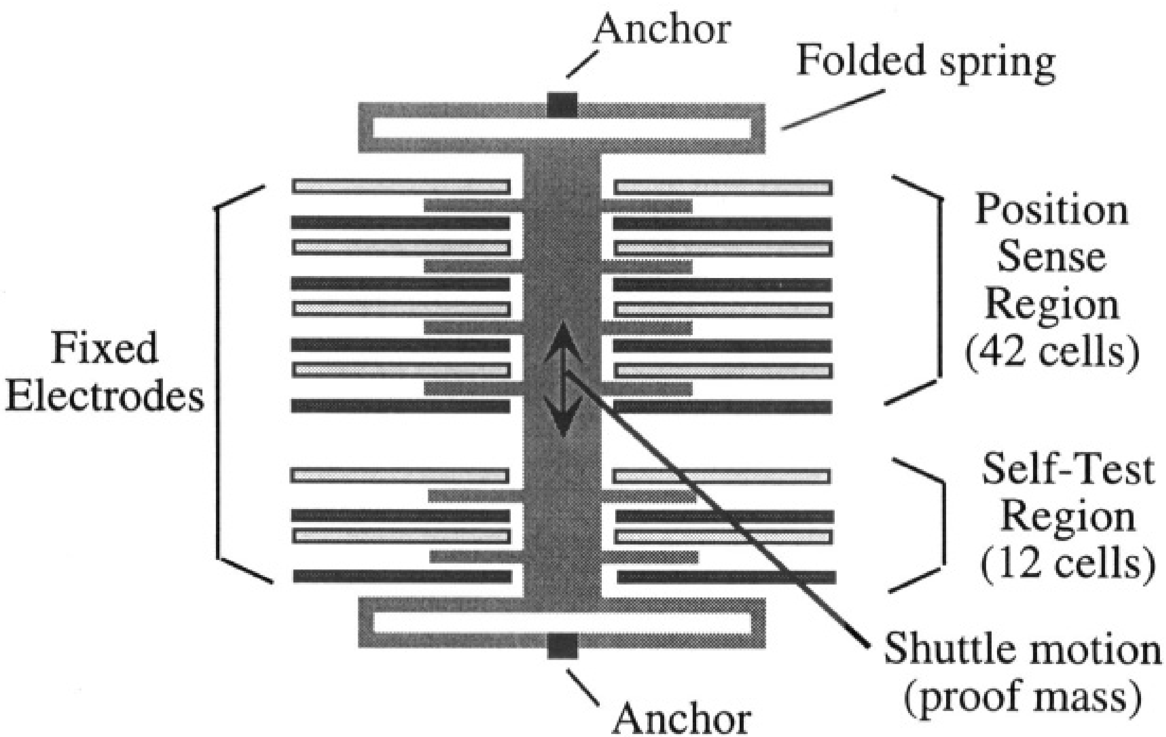


A Capacitive Accelerometer Case Study

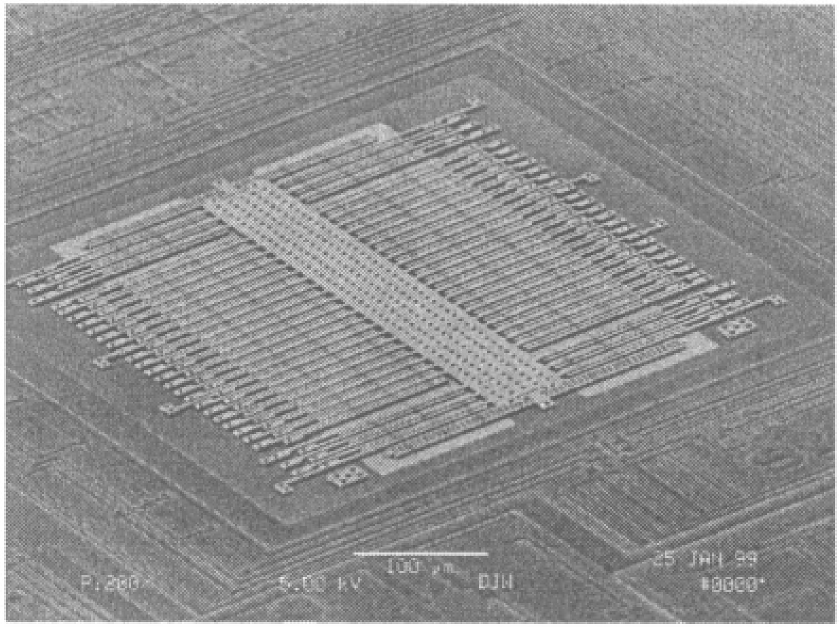
- Analog Devices (ADI) manufactures a family of surface-micromachined capacitive accelerometers. The devices are monolithic, having a single silicon chip that contains the micromachined proof-mass and spring supports and the circuitry that implements all of the electronic functions required to give an analog output signal proportional to acceleration.

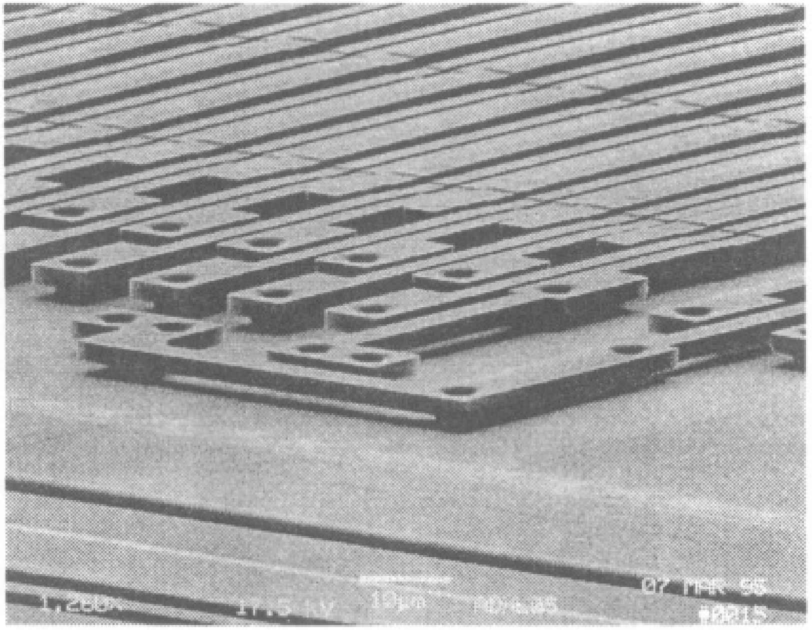


A Capacitive Accelerometer Case Study

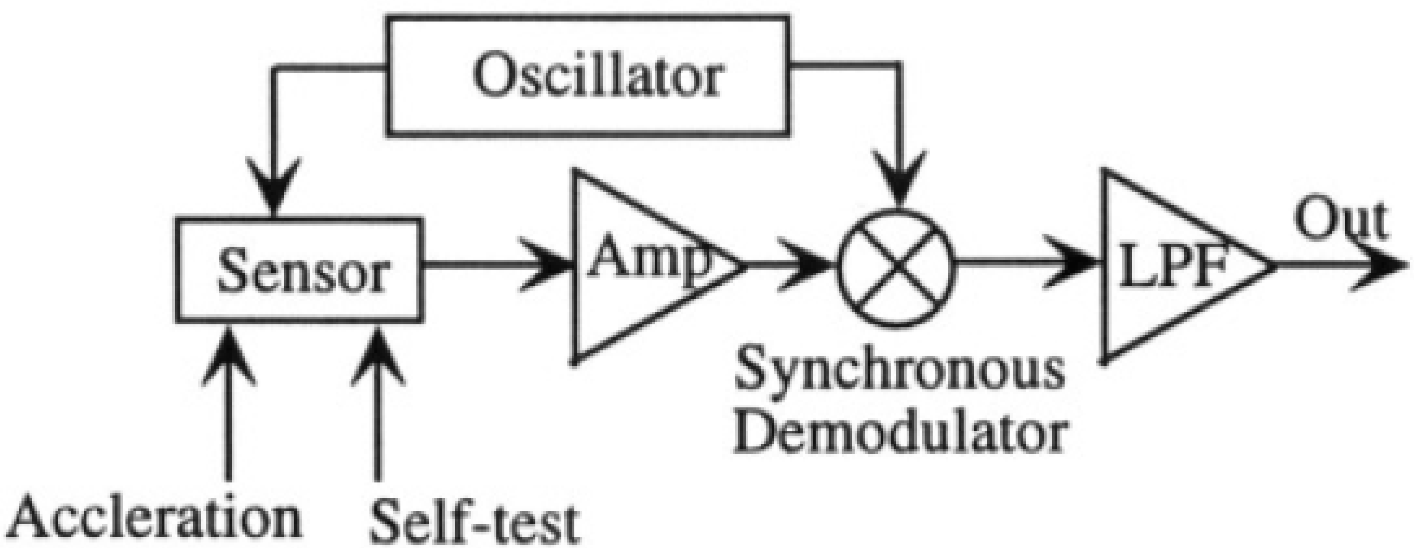


A Capacitive Accelerometer Case Study

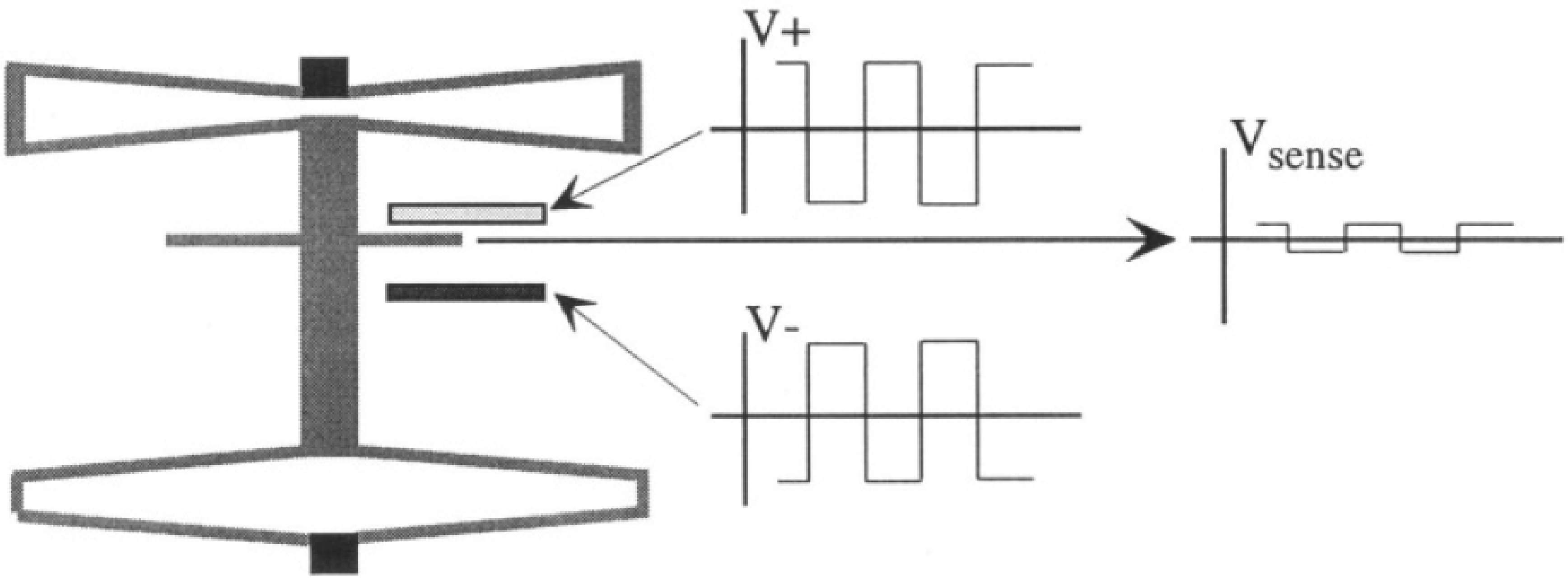




A Capacitive Accelerometer Case Study



A Capacitive Accelerometer Case Study

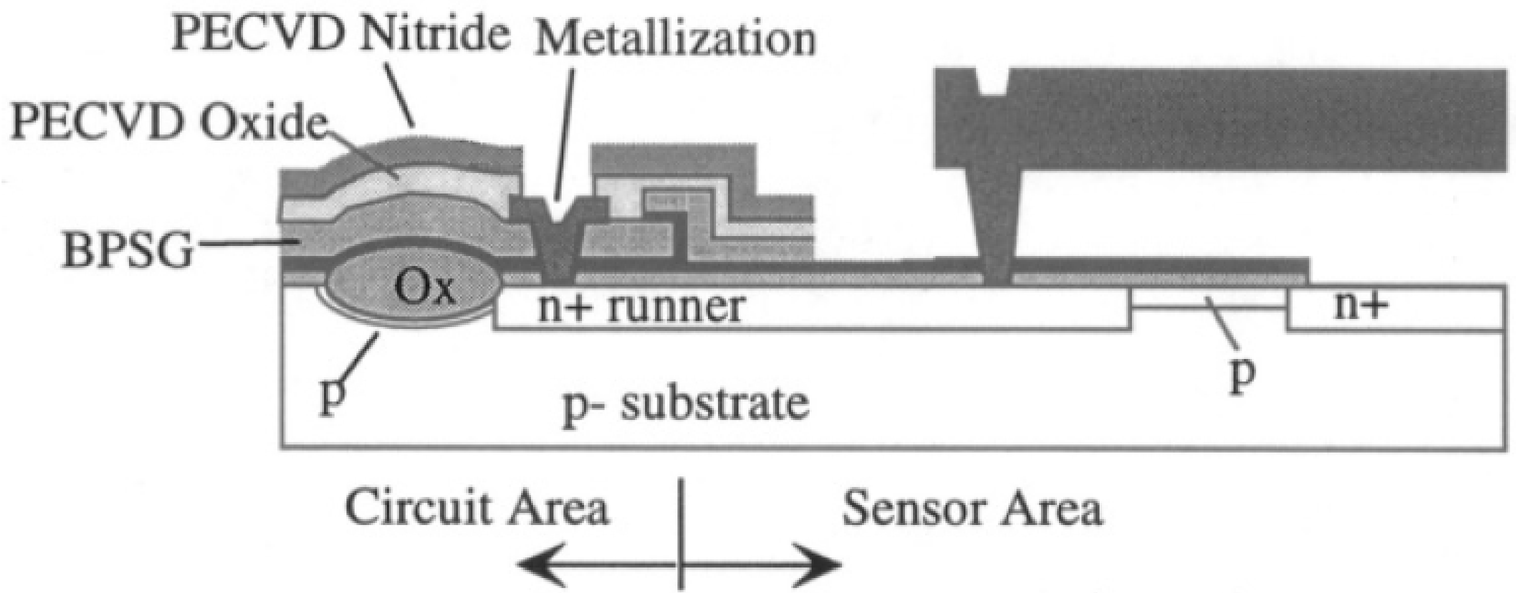


Property	Specification
Sensitivity	38mV/g
Full-scale range	$\pm$ 50 g
Transfer function form	see text
Package type	14-pin cerpak
Temperature range	-40 to +85°C
Supply voltage	4 - 6 V
Nonlinearity	0.2 %
Package alignment error	$\pm$ 1°
Transverse sensitivity	$\pm$ 2%
Zero-g output voltage (Bias)	$V_s/2 \pm 0.35$ V
Temperature drift (from 25°C to T_{min} or T_{max})	0.2 g
Noise from 10 Hz to nominal bandwidth	1 m$g/\sqrt{\text{Hz}}$
Clock noise	5 mV peak-to-peak
Bandwidth	400 or 1000 Hz, customer choice
Temperature drift of bandwidth	50 Hz
Sensor resonant frequency	24 kHz
Self test output change	400 mV
Absolute maximum acceleration	2000 g (unpowered)
	500 g (powered)
Drop test	1.2 meters
Min/max storage temperature	-65 to 150 °C
Max lead temperature (10 seconds)	245 °C

Fabrication and Packaging

- The ADXL150 accelerometer is fabricated in an Analog Devices process named iMEMS. The process combines MOS transistors, bipolar transistors, and polysilicon micromachined structures into a single process flow. A 1994 version of the process that is publicly documented used 24 masks, with 13 used for the electronics and 11 for the mechanical structure and interconnect to the electronics. It is interesting to examine the interface between the circuit and sensor areas in this process as an example of the intricacy of a fullymerged process designed to combine freely moving mechanical parts with fully protected electronic components.

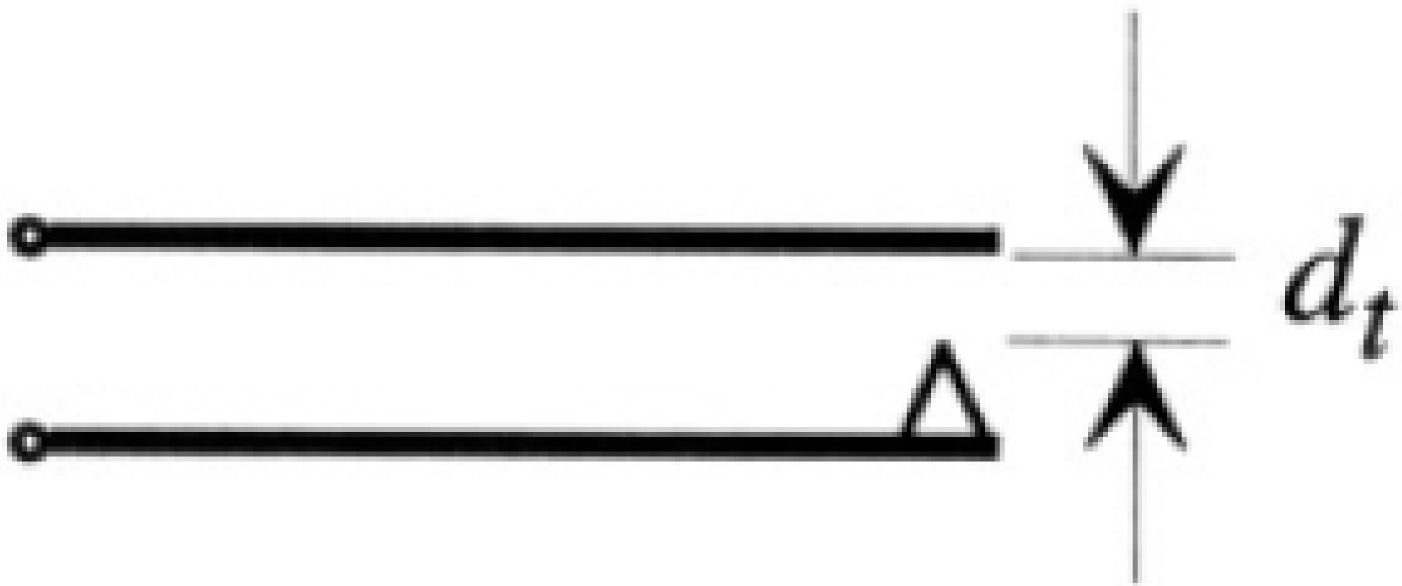
Fabrication and Packaging



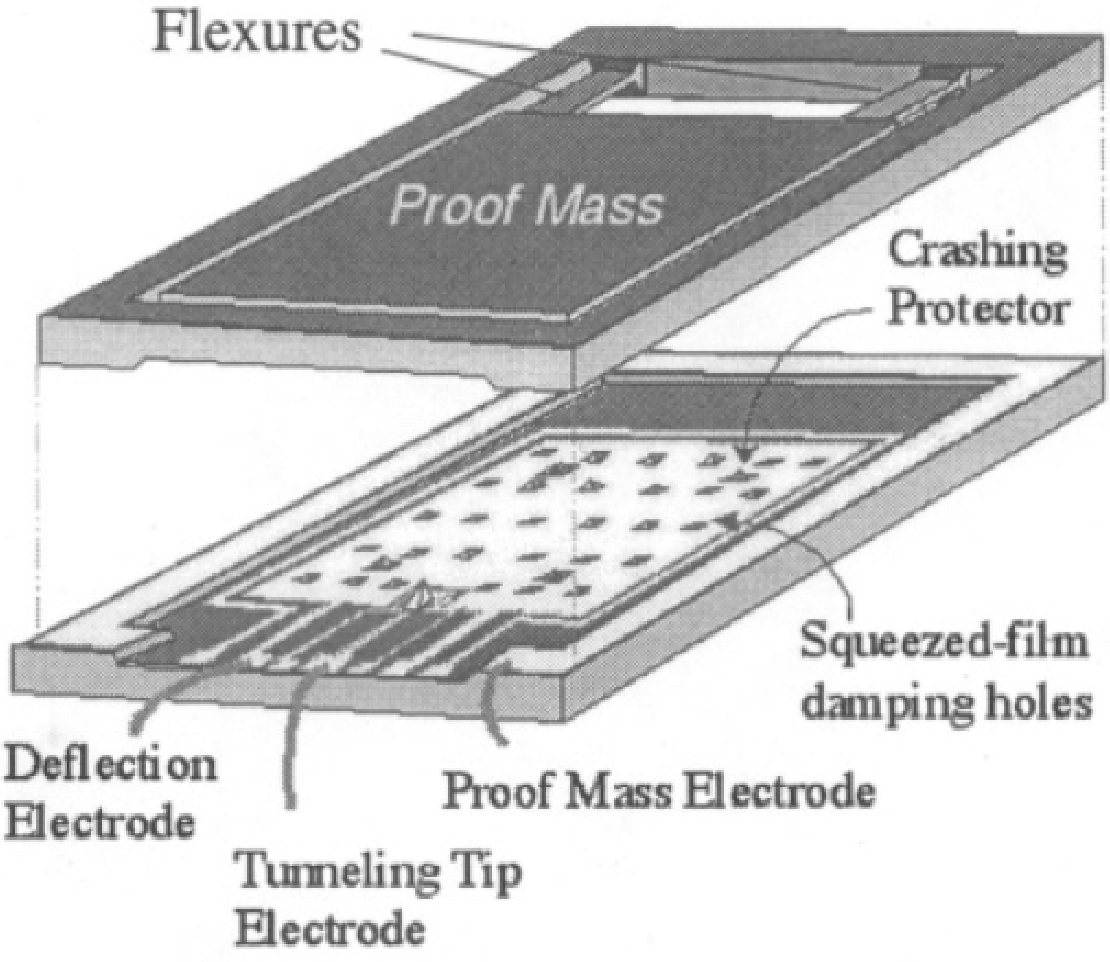
Position Measurement With Tunneling Tips

- Perhaps the most sensitive method for measuring position is to exploit the exponential dependence of current on the distance between an atomically sharp tunneling tip and an electrode. Scanning tunneling microscopes which use this principle are well-established commercially.
- Microfabrication of structures that incorporate tunneling tips permit the implementation of a wide varietyof sensors

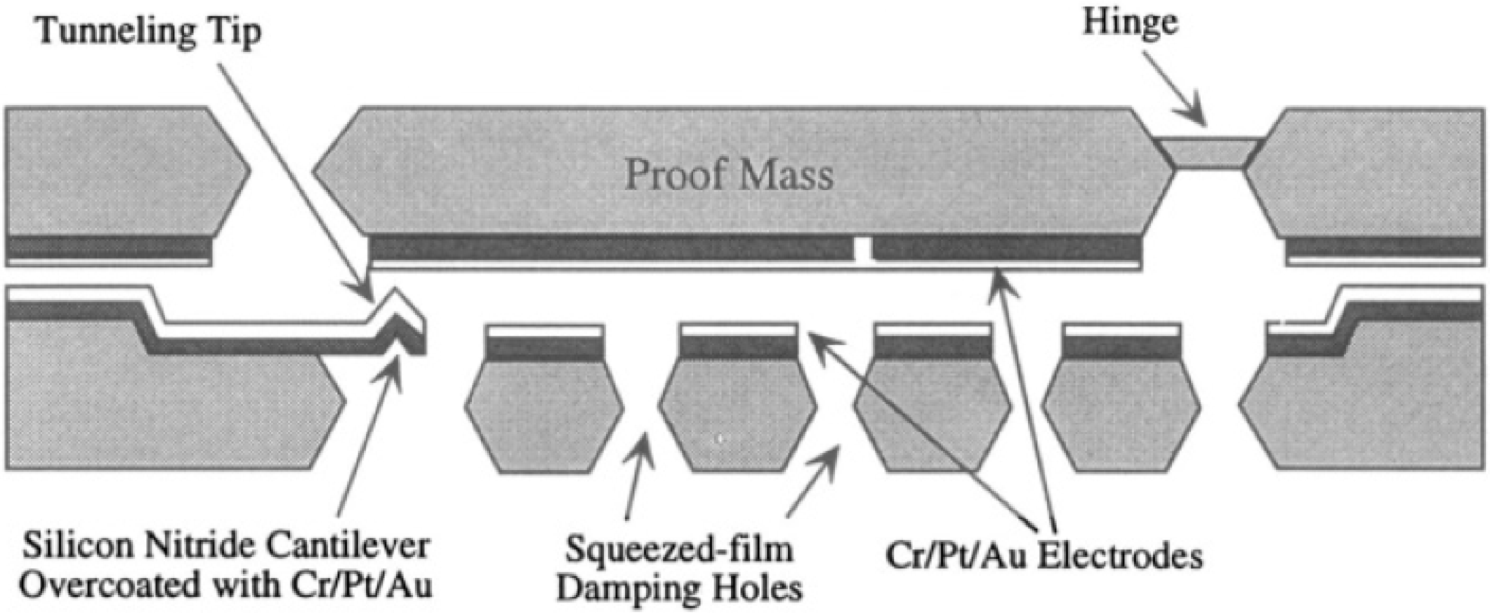
Position Measurement With Tunneling Tips



Position Measurement With

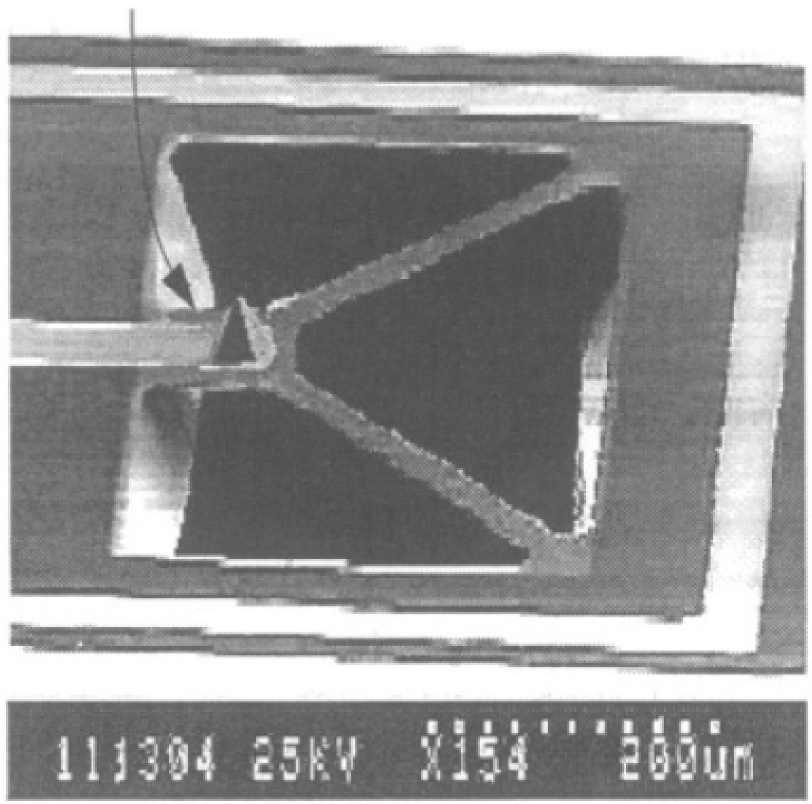


Position Measurement With Tunneling Tips



Position Measurement With Tunneling Tips

Nitride cantilever with tunneling tip



ELECTROSTATIC PROJECTION DISPLAYS

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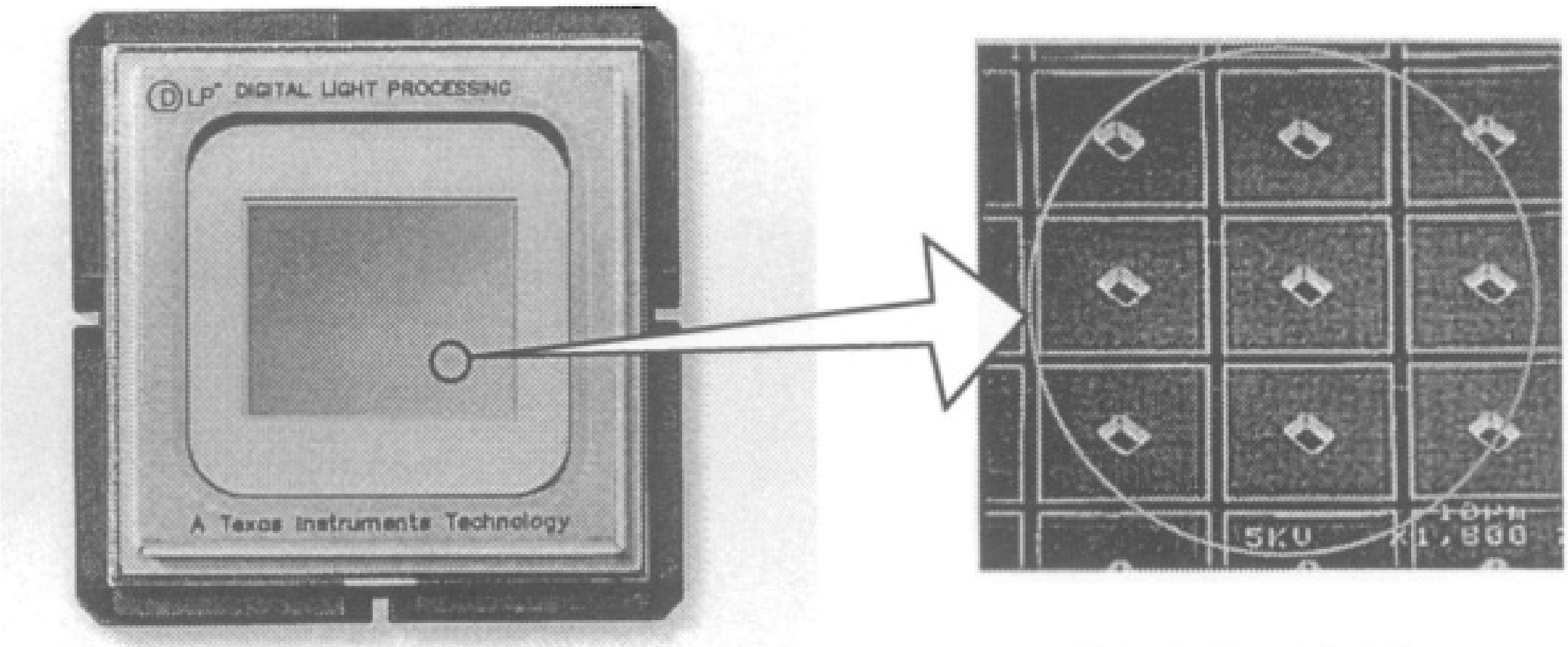
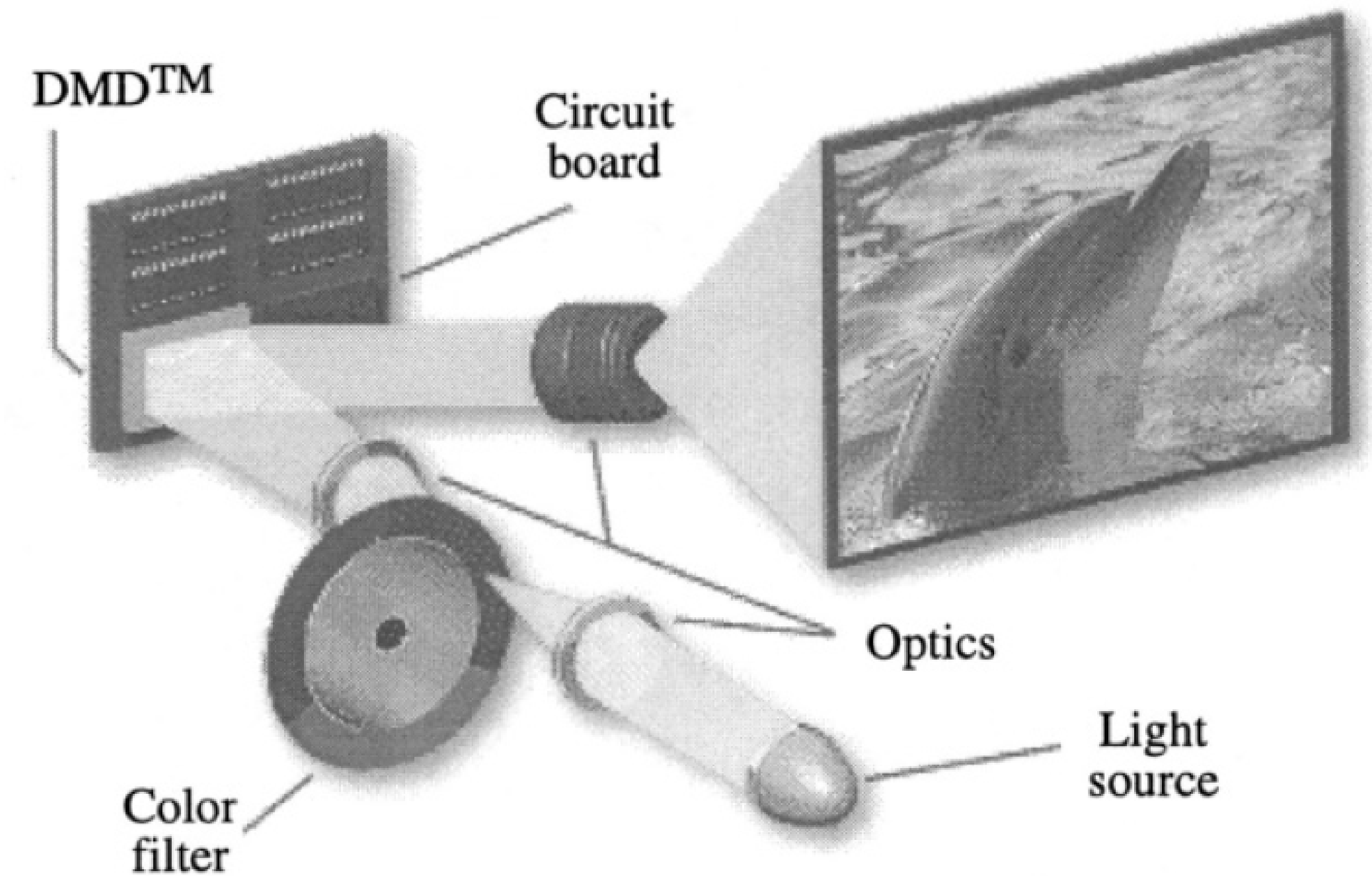


1,310,720 mirror pixels
(1280 x 1024)

9 mirror pixels

ELECTROSTATIC PROJECTION DISPLAYS



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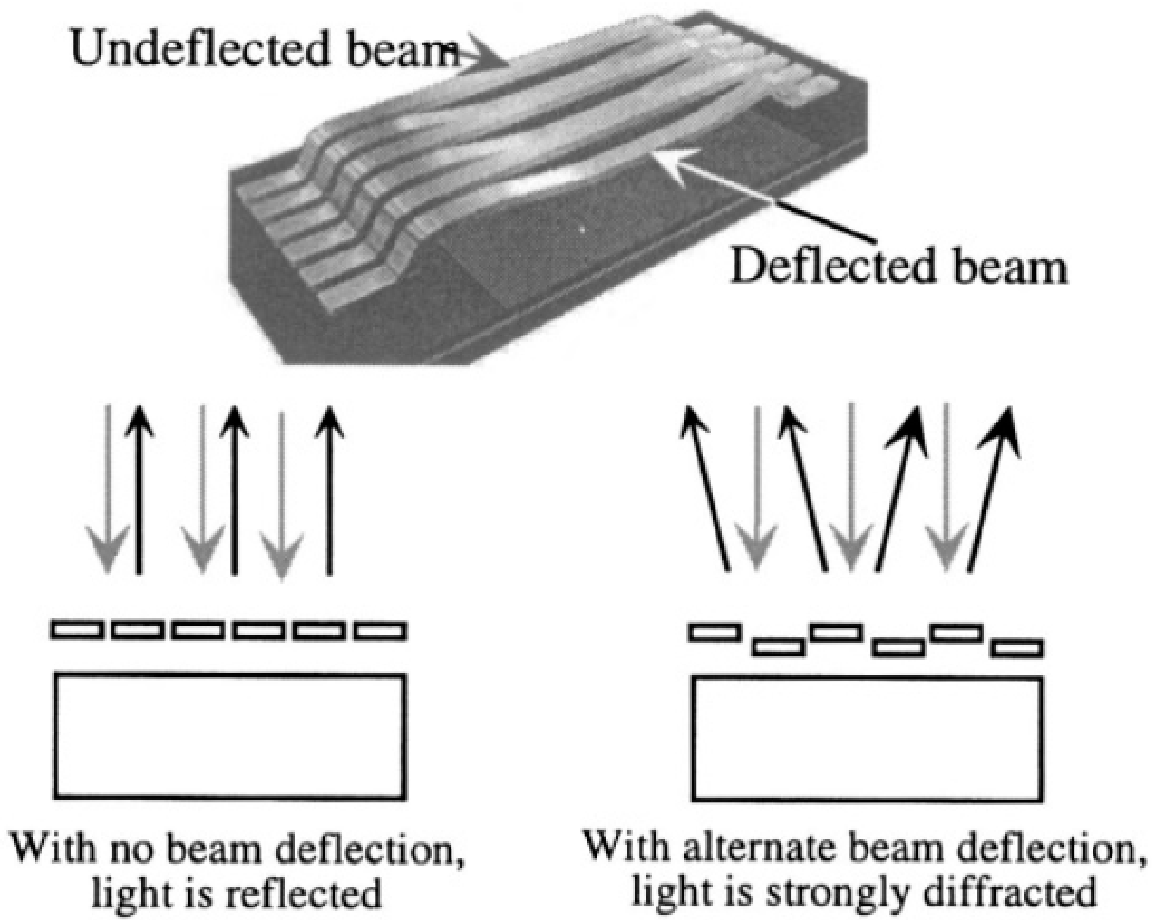

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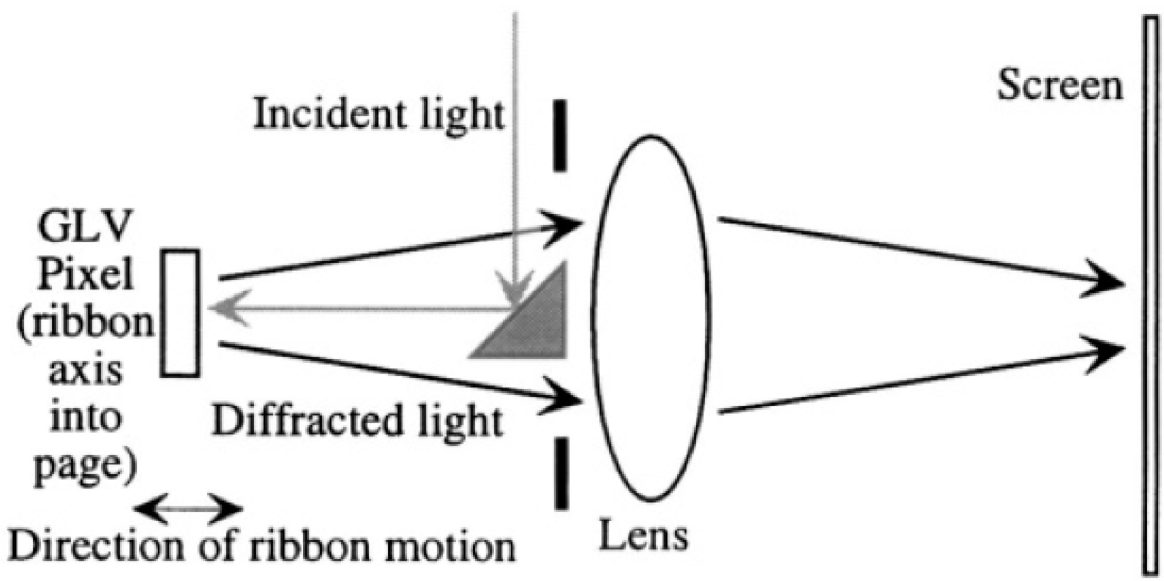

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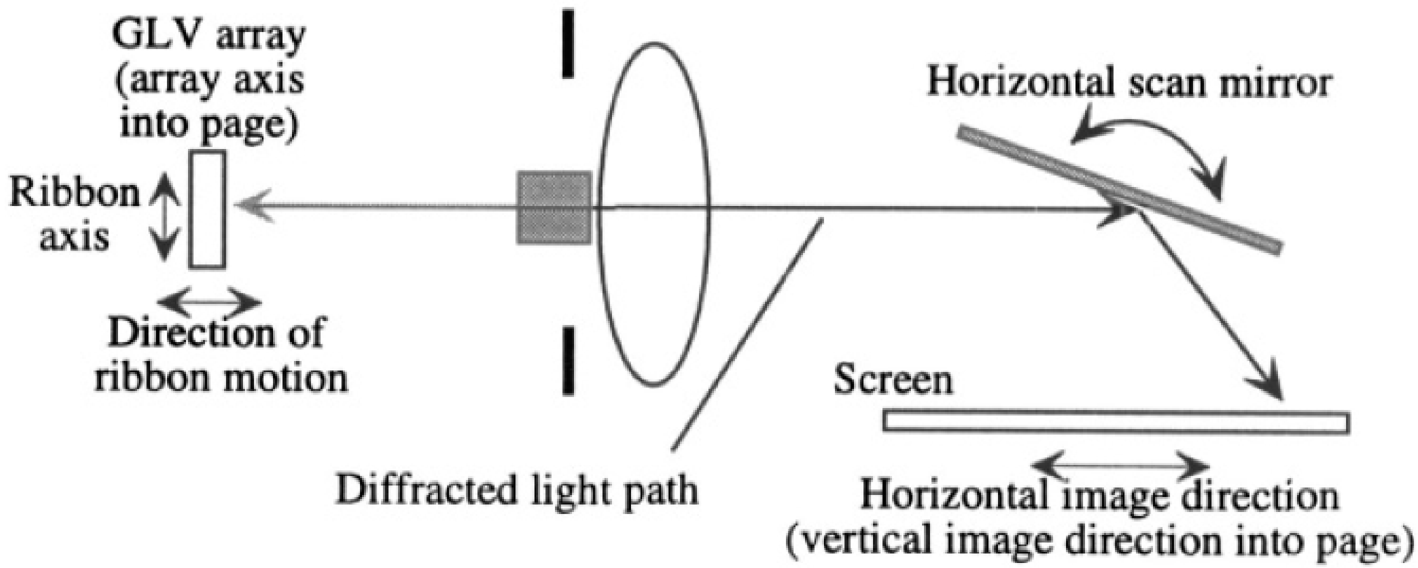

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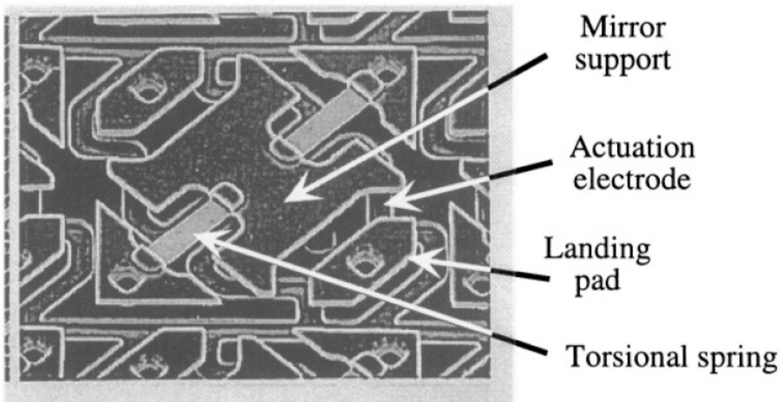

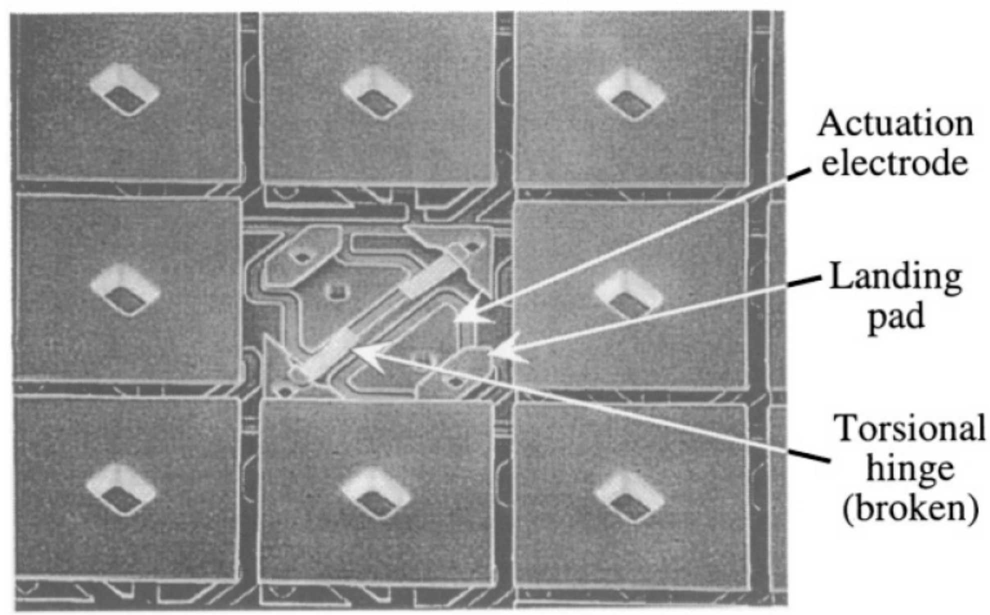

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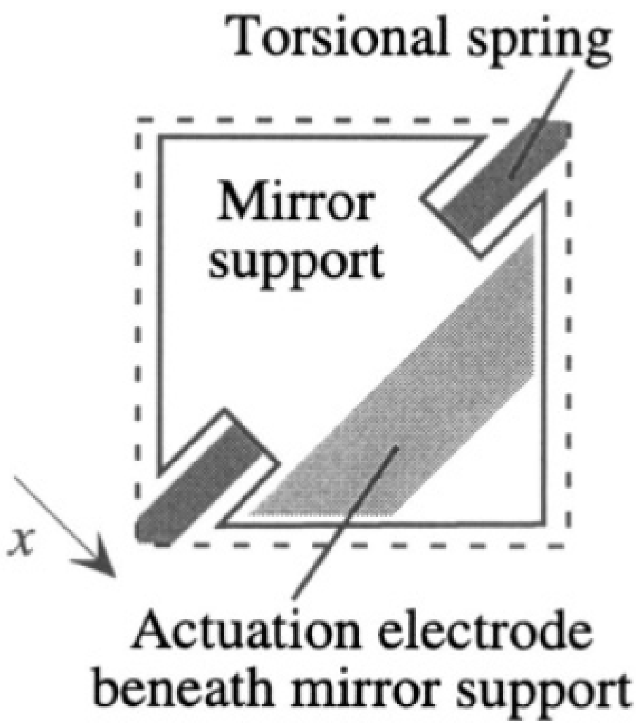
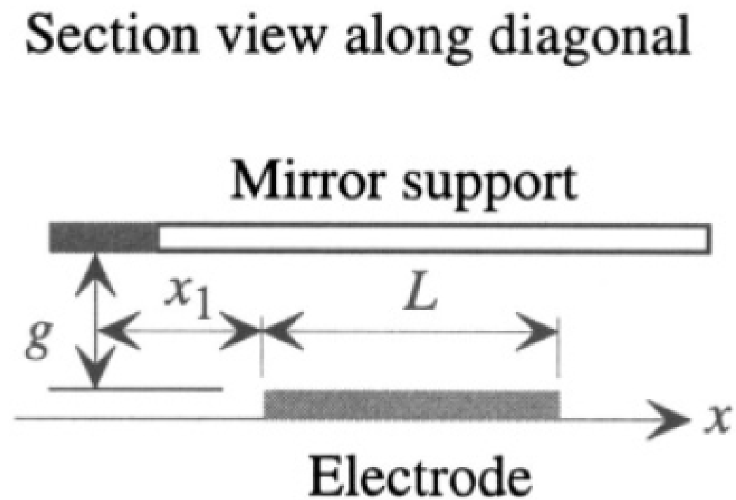
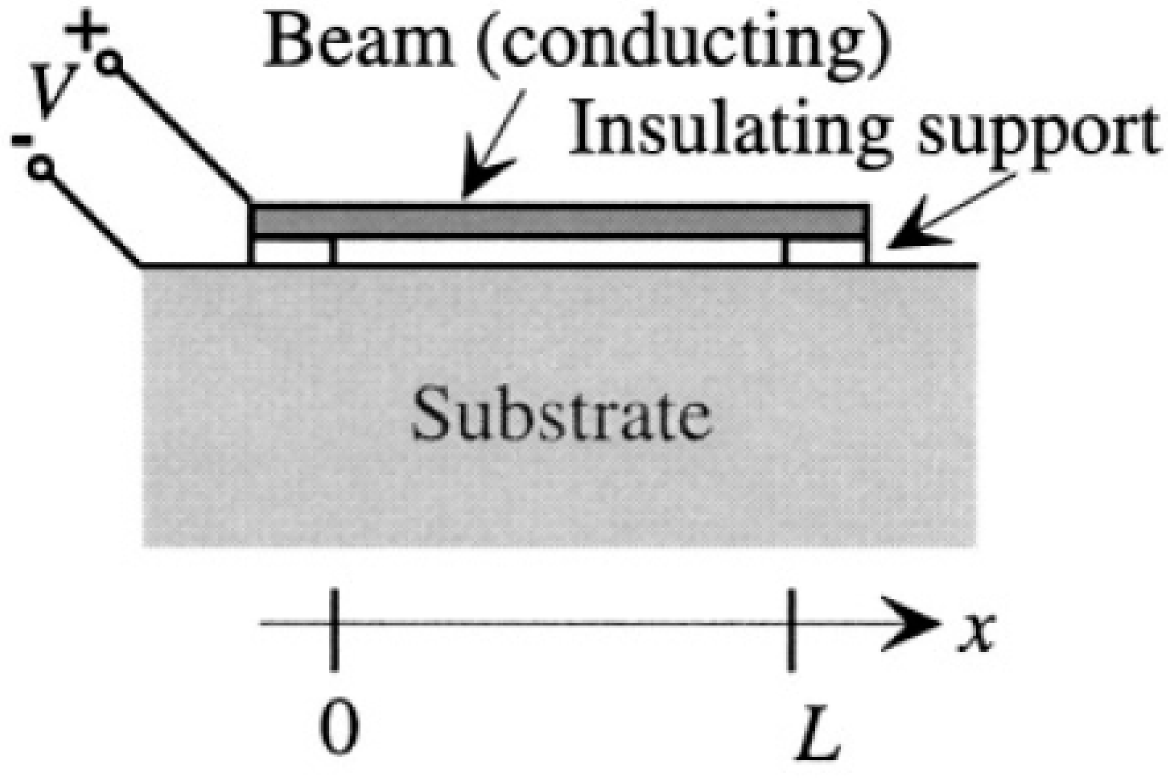
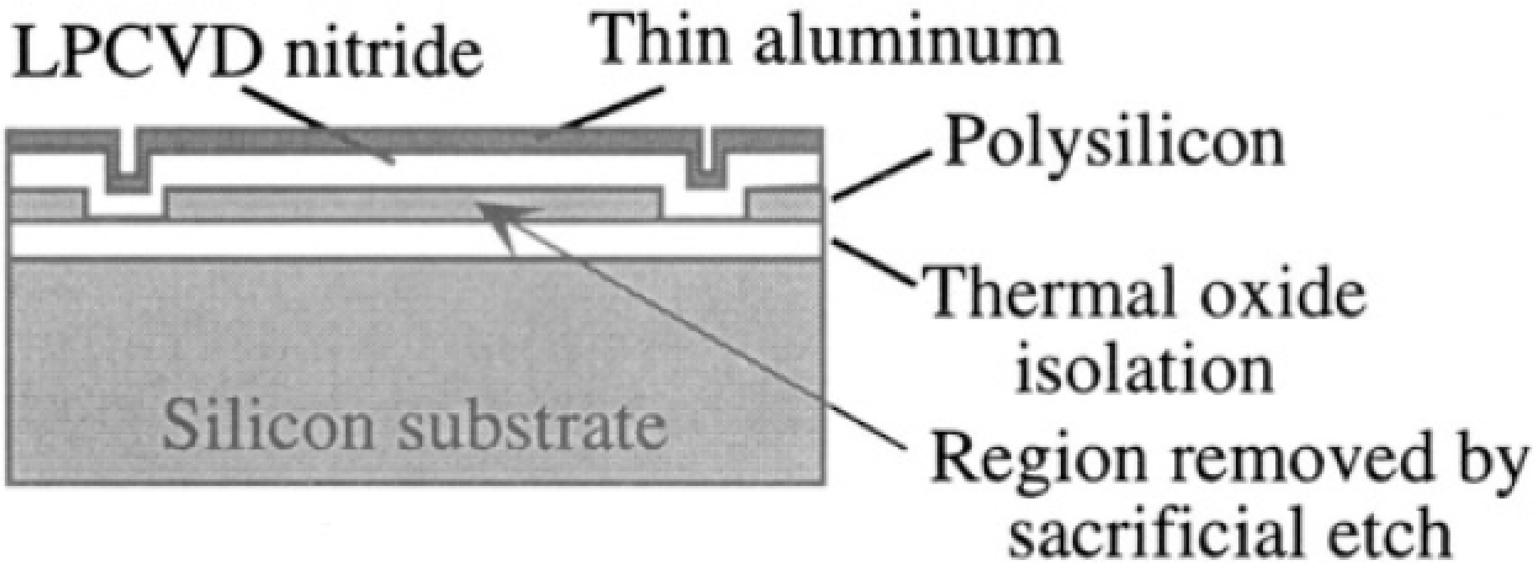




Electromechanics of Electrostatically Actuated Beams



Device Fabrication and Packaging



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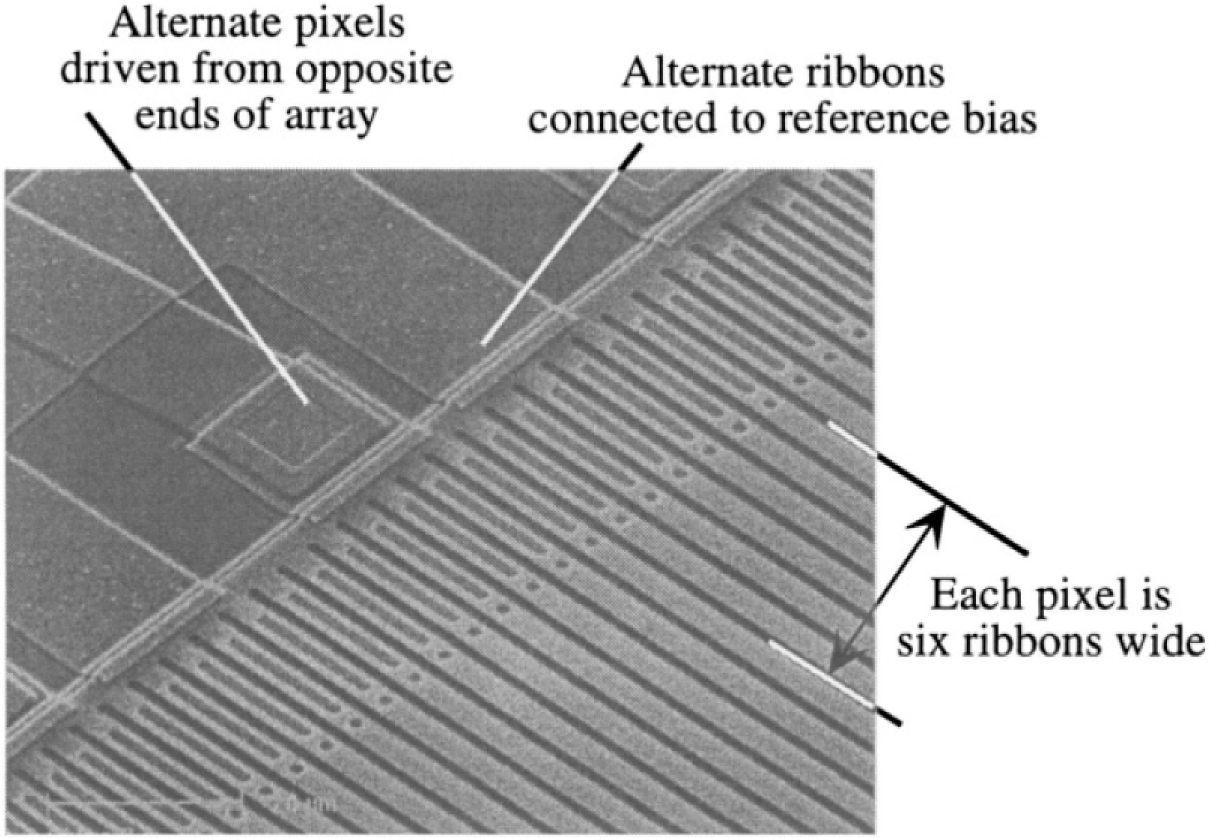

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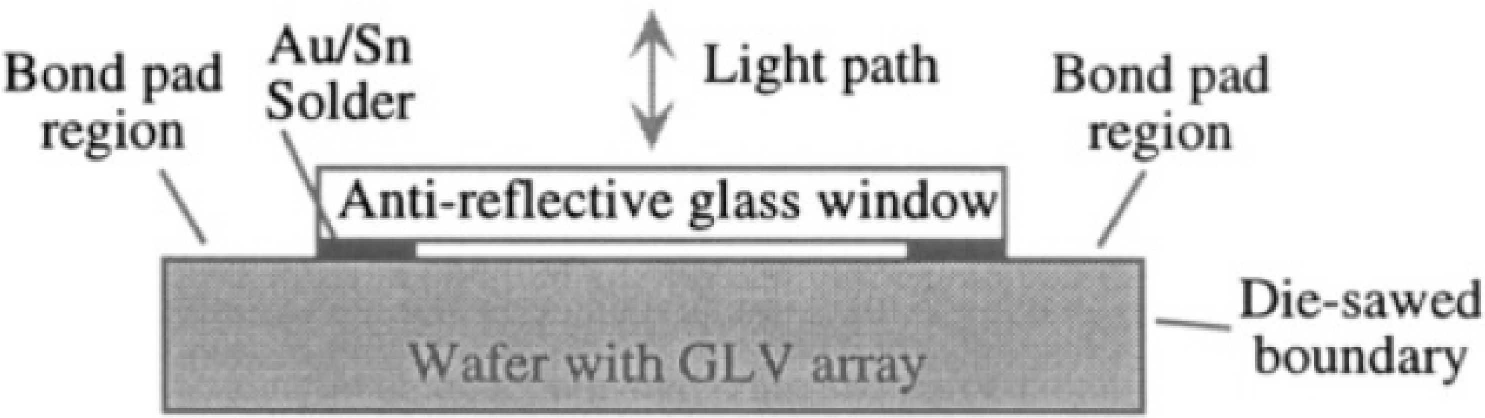
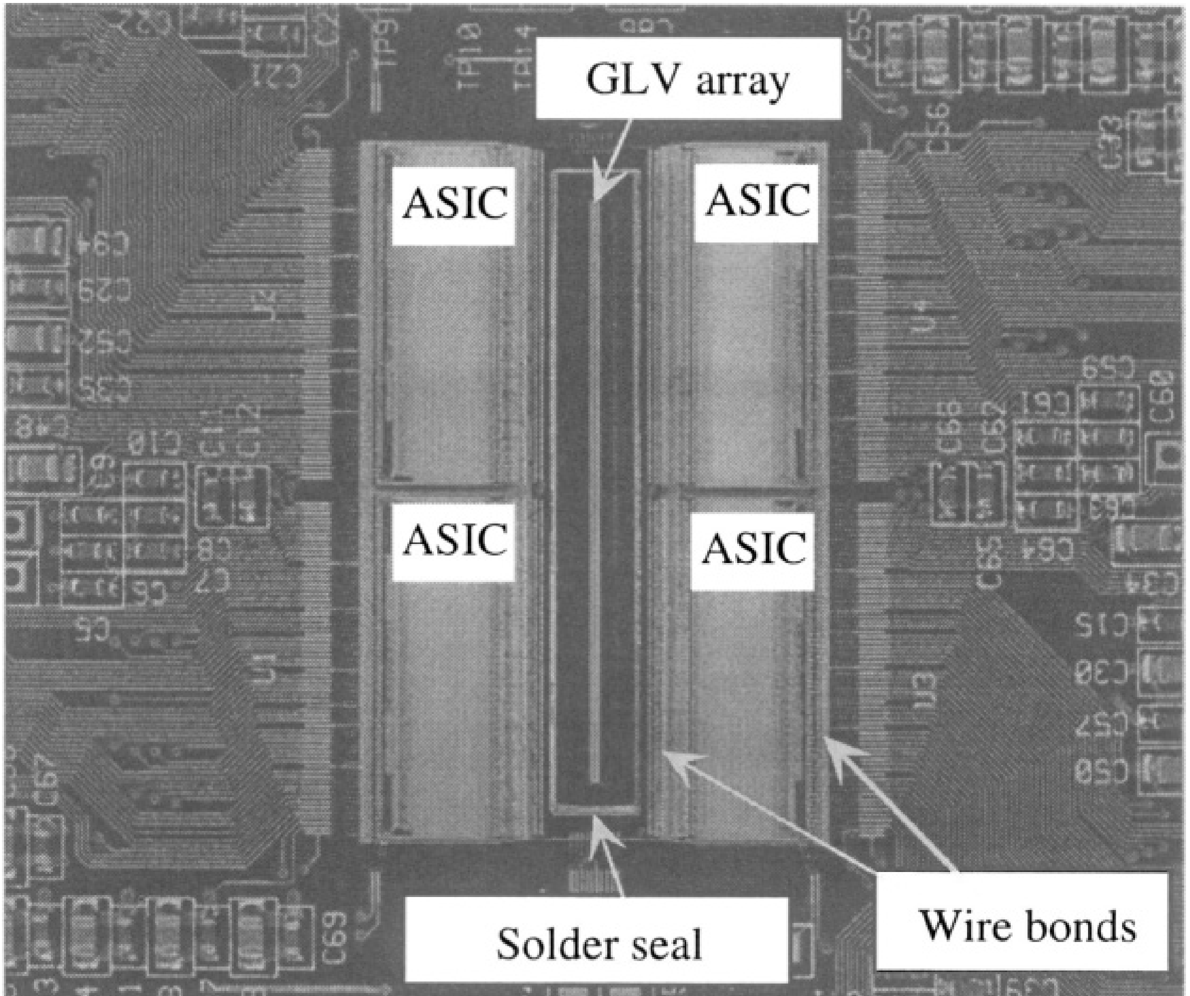


Device Fabrication and Packaging



PIEZOELECTRIC RATE GYROSCOPE

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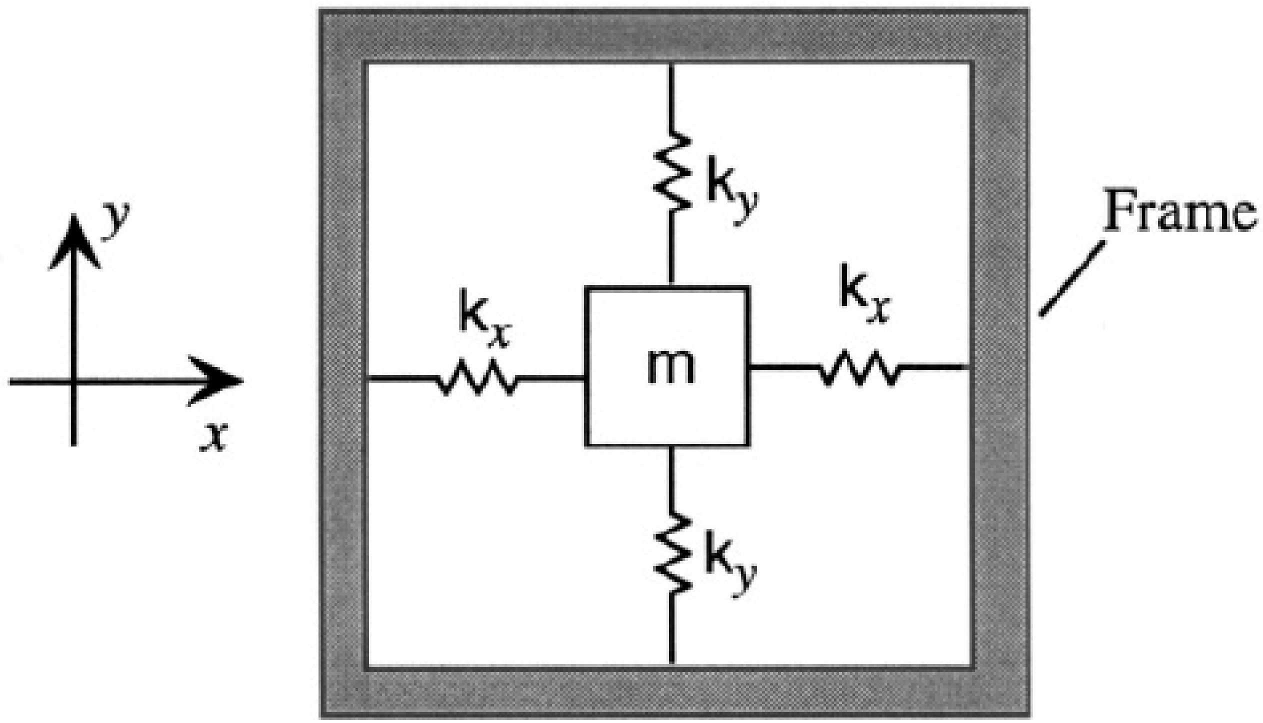
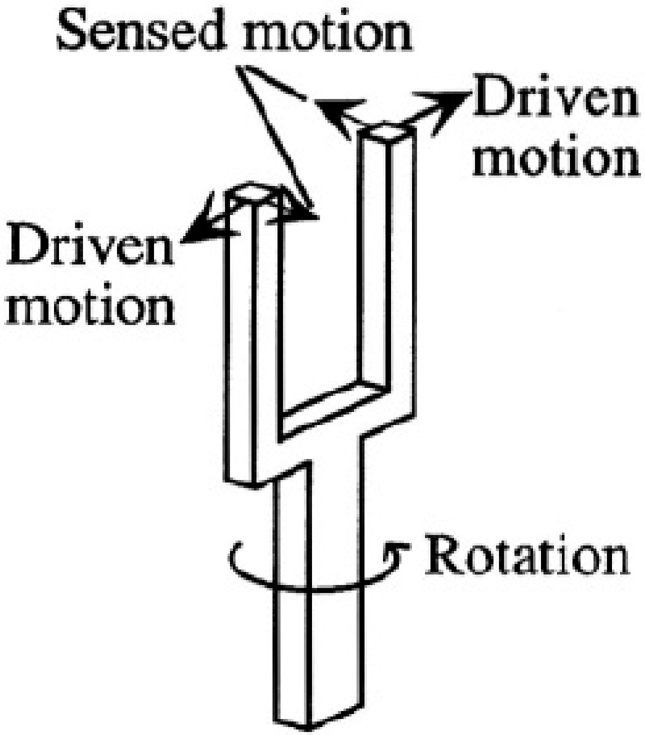
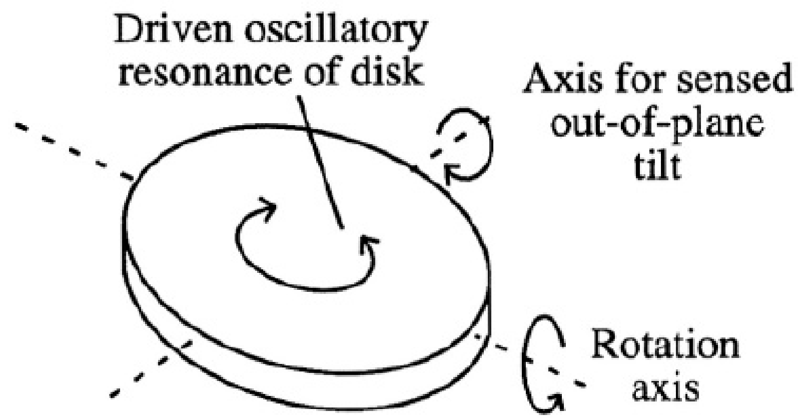
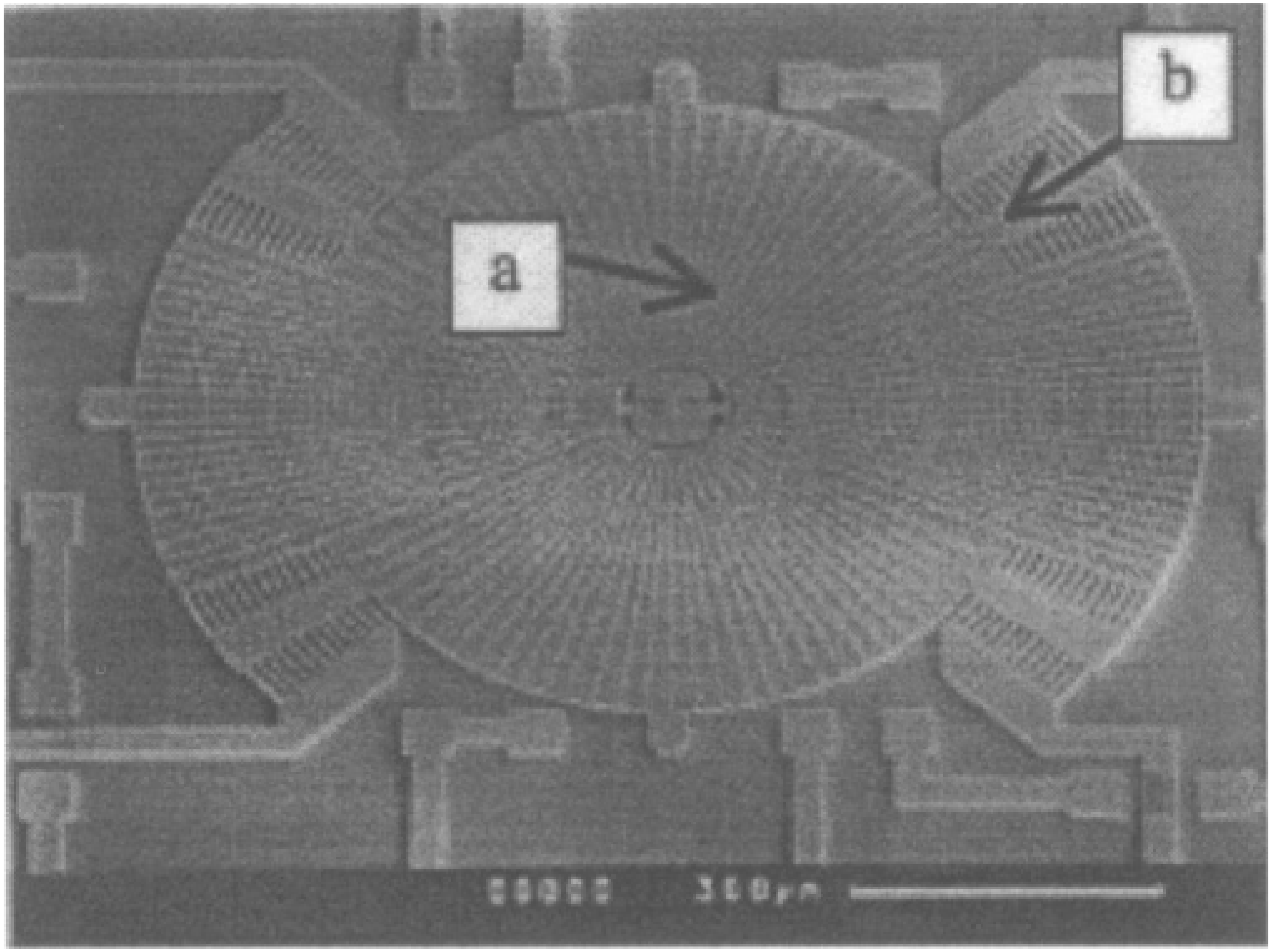


Generalized Gyroscopic Modes

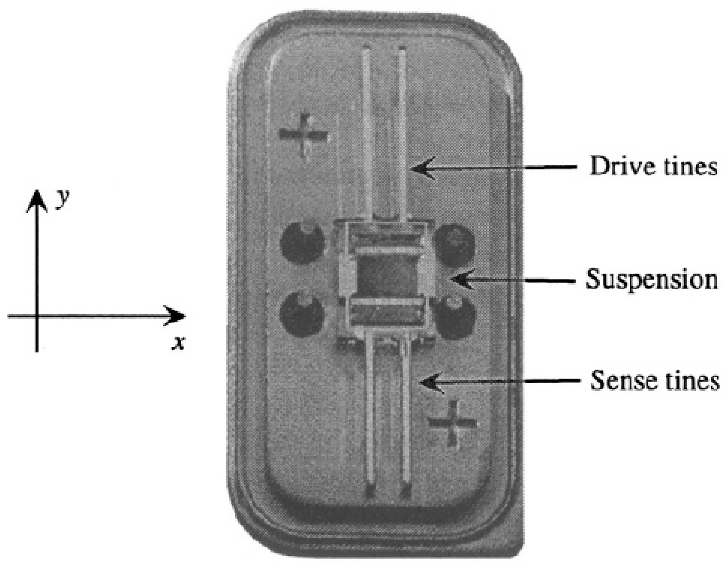


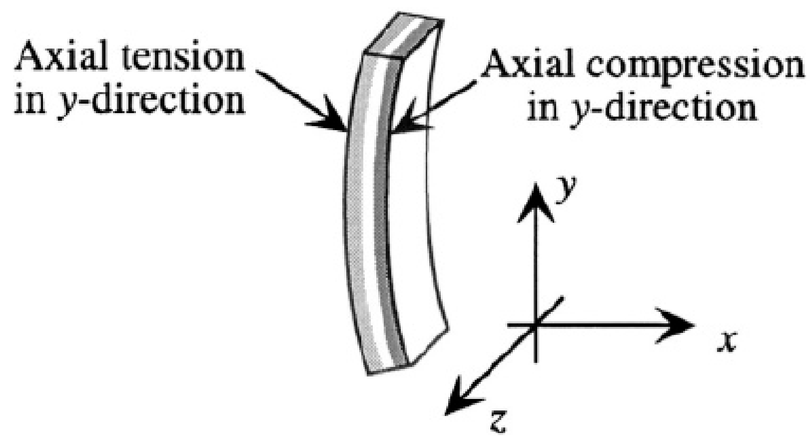


Resonant Gyroscope

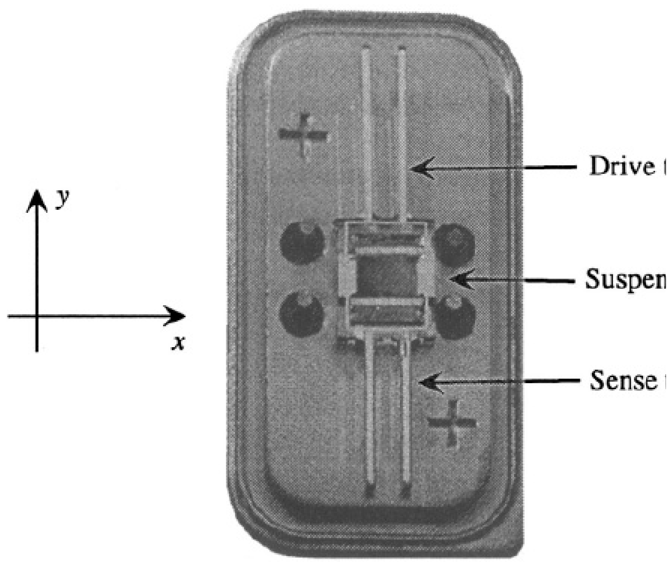


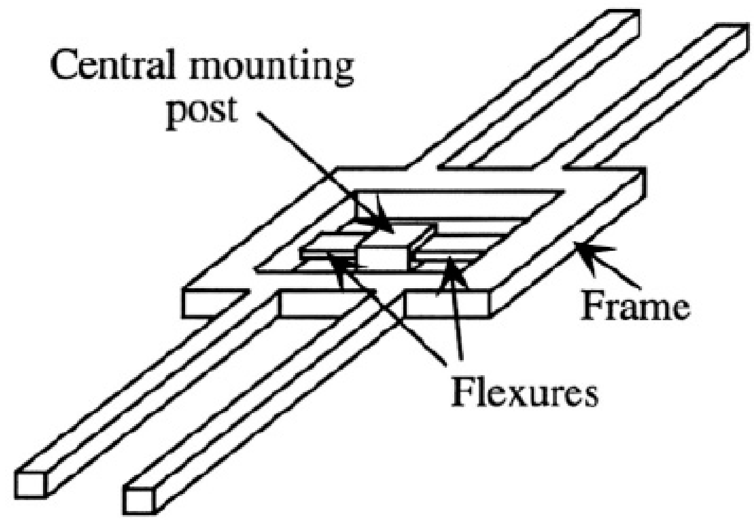
Quartz Rate Gyroscope Case Study



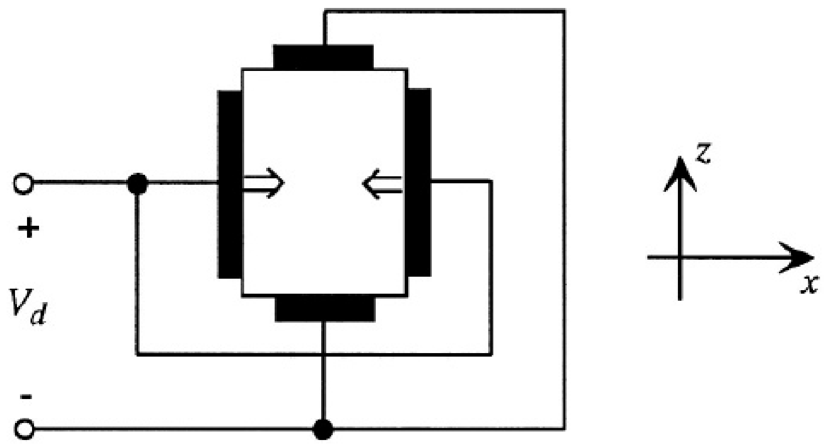


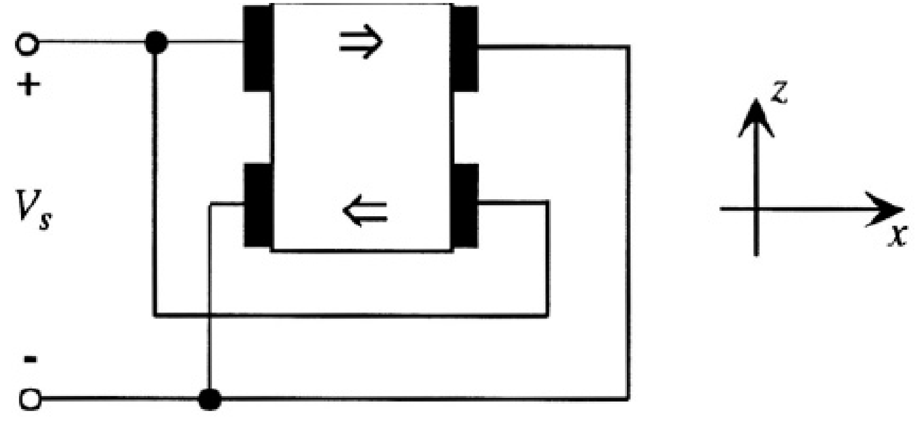
Quartz Rate Gyroscope Case Study



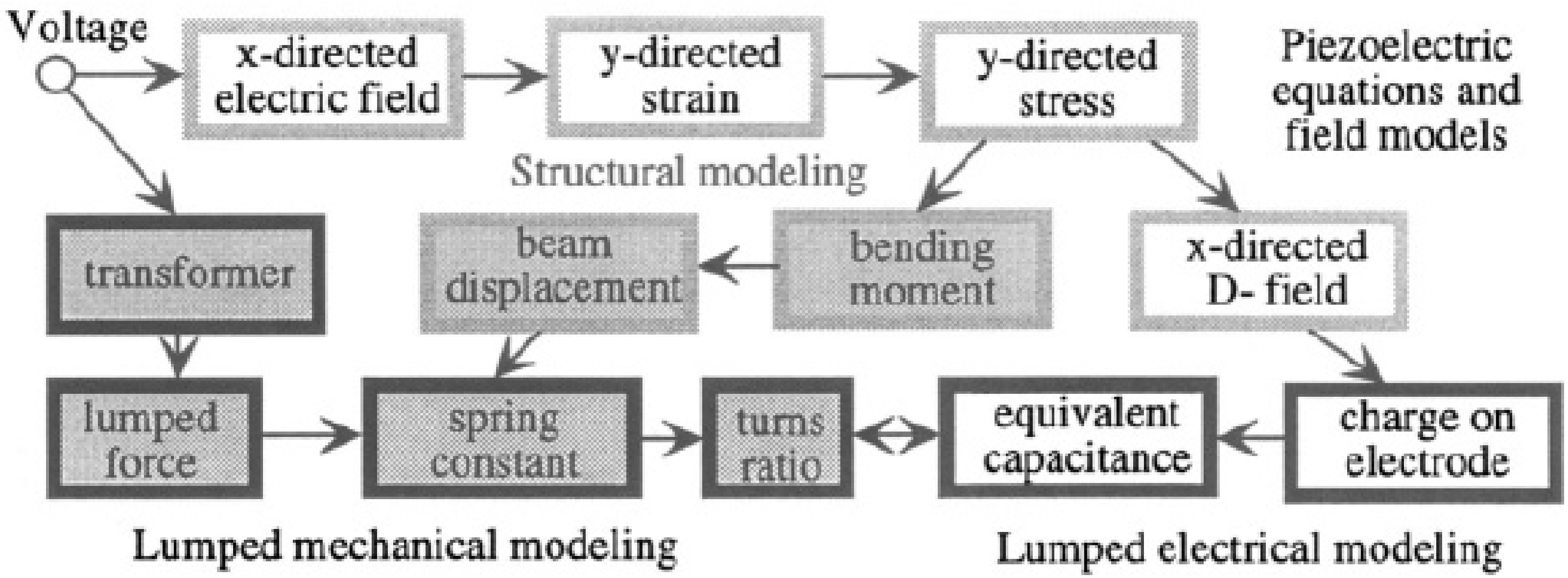


Quartz Rate Gyroscope Case Study





Processing Sinal



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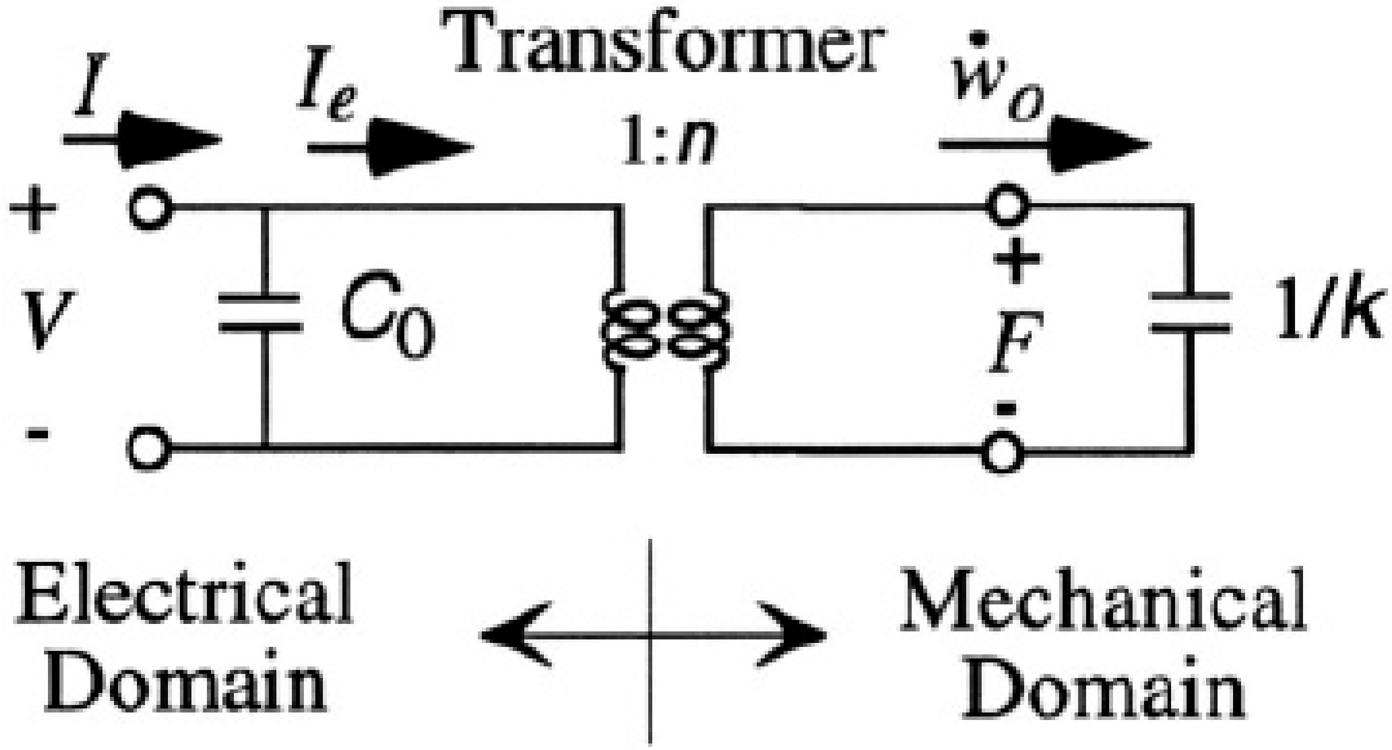

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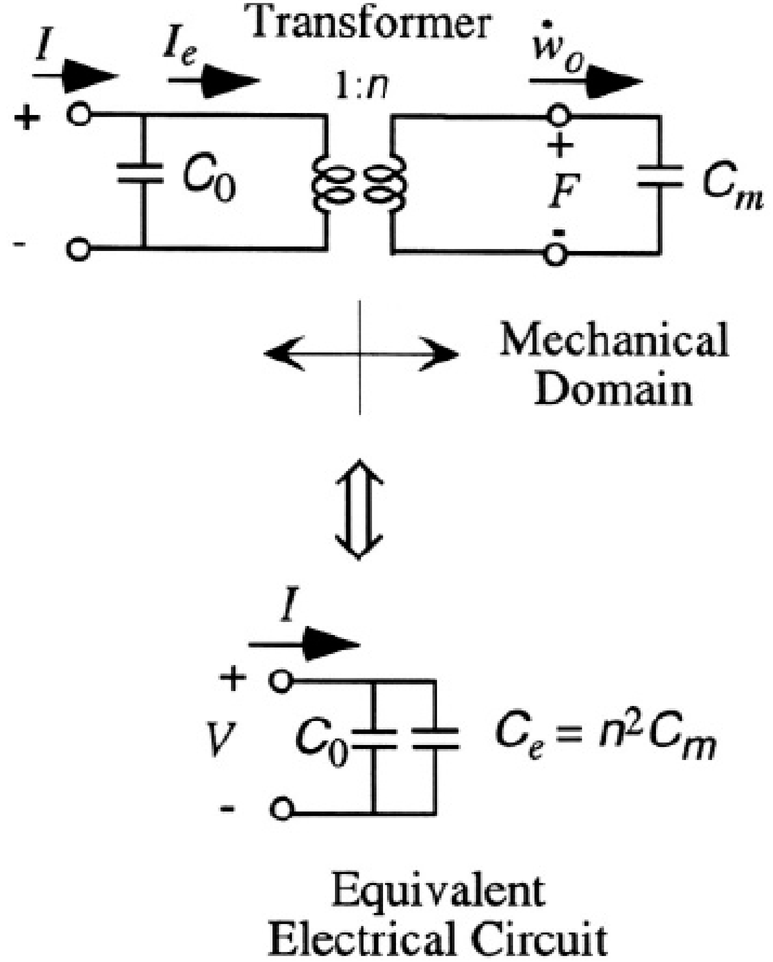

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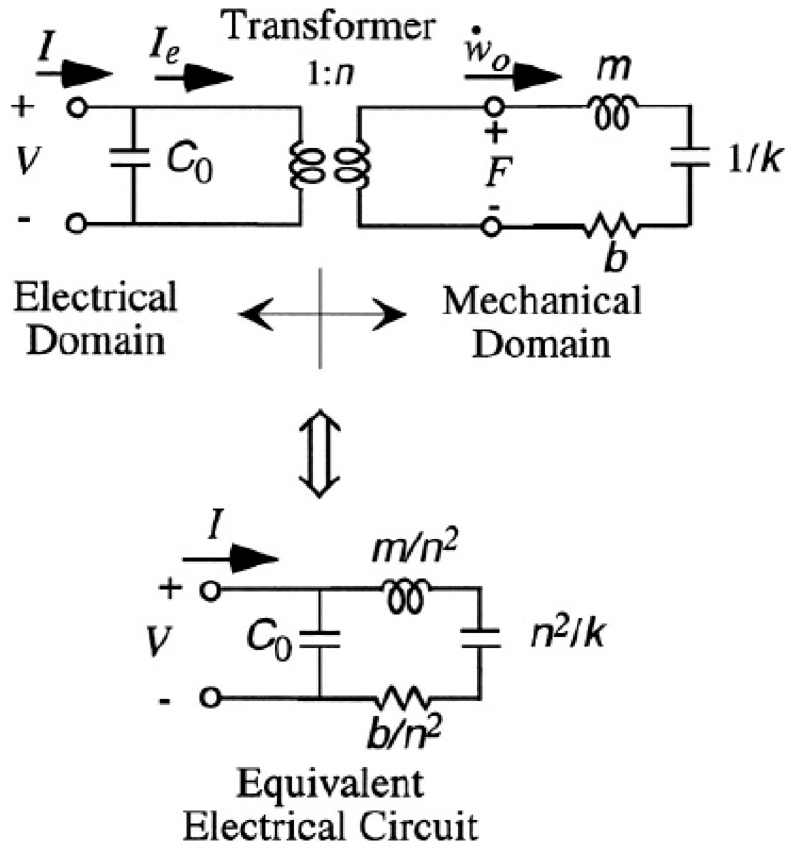
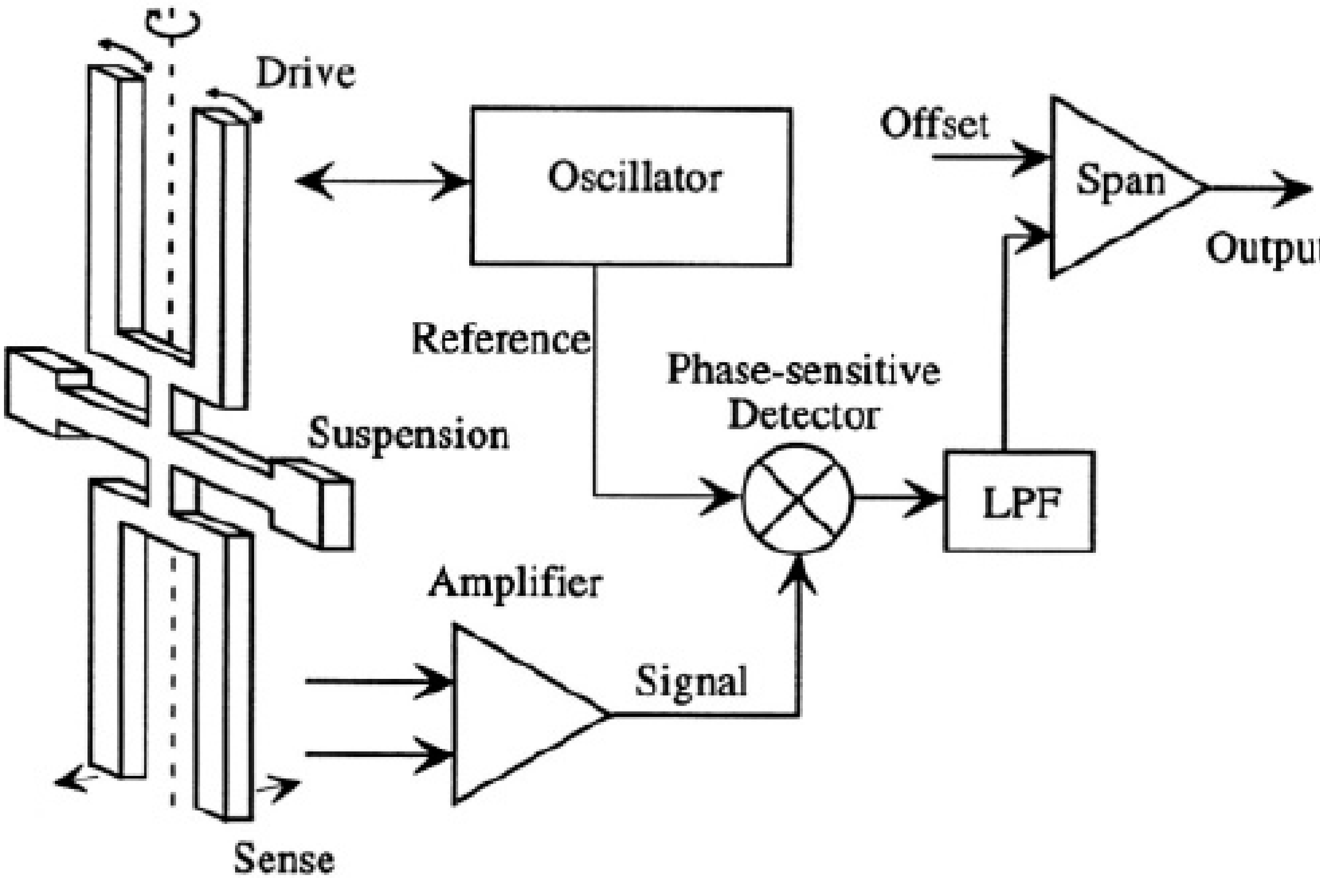


Angular Sensor



Angular Sensor

Parameter	Specification
Input voltage	5 V DC ± 5%
Input current	< 20 mA
Standard ranges	± 64°/sec
Full range output	0.025 to 4.75 V DC
Scale factor calibration (at 22 °C)	± 3% (including temp)
Offset bias	2.50 V DC
Bias variation over temperature	< 4.5°/sec
Short-term bias stability *(100 sec at const temp)*	< .05°/sec
Long-term bias stability	< 1.0°/sec
g-sensitivity	< .06°/sec/g
Bandwidth	> 50 Hz
Nonlinearity	< 0.05% of full range
Threshold/resolution	< .004°/sec
Output noise (DC to 100 Hz)	< 0.025°/sec/$\sqrt{\text{Hz}}$
Operating temperature	-40°C to 85°C
Storage temperature	-55°C to 100°C
Vibration (operating)	1.5 g_{RMS} 20 Hz to 2 kHz random
Vibration (survival)	10 g_{RMS} 20 Hz to 2 kHz random
Shock	200 g