Lecture 6: Piezoelectricity & Piezoresistivity

The Piezoelectric Effect

Some crystal would electrically polarize when deformed by an applied force. When equal and opposite forces F_1 and F_2 (generating tensile stresses) are applied as shown in figure 1, the resulting deformation of the crystal lattice produces a separation of the centers of gravity of positive and negative charges.

This microscopic separation produces electrical dipoles within the crystal, and, in some materials, these dipoles moments combine to give an average microscopic moment or electrical polarization. This net electrical charge appears on the surface of the electrodes. When the forces are removed, the strain within the crystal lattice is released, causing the charge to flow. This phenomenon is known as the direct piezoelectric effect.

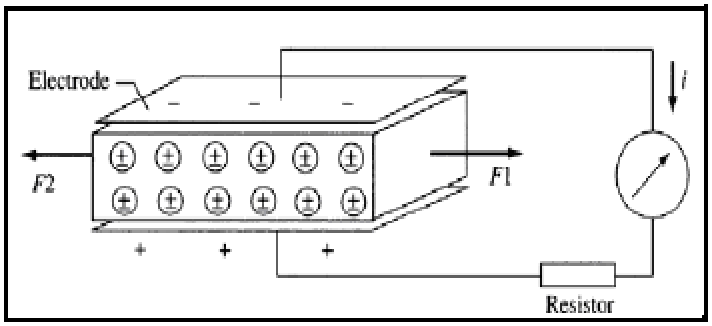


Figure 1: Transformation of mechanical energy into electrical energy

The direct piezoelectric effect is always accompanied by the inverse effect in which the material will become strained when it is placed in an external field. When an external voltage is applied to the electrodes, the crystal lattice will deform by an amount proportional to the applied voltage. In this case, the electrical energy is transformed into mechanical energy, and the device becomes a piezoelectric actuator. Two important properties justify the use of piezoelectricity in sensing applications:

i) An ideal coupling between the electrical and mechanical properties ensures a distortion-free transduction with extremely low dissipation.

ii) The anisotropic nature of piezoelectric crystals allows for different angles of cut and thus the design of devices operating over a wide range of frequencies.

History

In 1880, the brothers Pierre Curie and Jacques Curie predicted and demonstrated piezoelectricity using tinfoil, glue, wire, and magnets. They showed that crystals of tourmaline, quartz, topaz, and Rochelle salt (sodium potassium tartrate tetrahydrate) generate electrical polarization from mechanical stress. Quartz and Rochelle salt exhibited the most piezoelectricity.

Converse piezoelectricity was mathematically deduced from thermodynamic principles by Lippmann in 1881. The Curies immediately confirmed the existence of the "converse effect," and went on to obtain quantitative proof of the complete reversibility of electro-elasto-mechanical deformations in piezoelectric crystals.

The first practical application for piezoelectric devices was sonar, first developed during World War I. In France in 1917, Paul Langevin (whose development now bears his name) and his coworkers developed an ultrasonic submarine detector. The detector consisted of a transducer, made of thin quartz crystals carefully glued between two steel plates, and a hydrophone to detect the returned echo. By emitting a high-frequency chirp from the transducer, and measuring the amount of time it takes to hear an echo from the sound waves bouncing off an object, one can calculate the distance to that object.

The use of piezoelectricity in sonar, and the success of that project, created intense development interest in piezoelectric devices. Over the next few decades, new piezoelectric materials and new applications for those materials were explored and developed.

Development of piezoelectric devices and materials in the United States was kept within the companies doing the development, mostly due to the wartime beginnings of the field, and in the interests of securing profitable patents. Quartz crystals were the first commercially exploited piezoelectric material, but scientists searched for higher-performance materials.

In contrast, Japanese manufacturers shared their information, quickly overcoming technical and manufacturing challenges and creating new markets. Japanese efforts in materials research created piezoceramic materials competitive to the U.S. materials, but free of expensive patent restrictions.

Piezoelectric Materials

The most commonly used piezoelectric materials are bulk ceramics. They are created by taking a powder of piezoelectric particles and compressing them under high pressure and temperature. Many materials exhibit the effect, including quartz analogue crystals like berlinite ($AlPO_4$) and gallium orthophosphate ($GaPO_4$), ceramics with perovskite or tungsten-bronze structures ($BaTiO_3$, $SrTiO_3$, $PbZrTiO_3$, $KNbO_3$, $LiNbO_3$, $LiTaO_3$).

Applications

Piezoelectric materials have a broad range of potential uses like:

a) High-voltage sources:

Direct piezoelectricity of some substances like quartz, as mentioned above, can generate potential differences of thousands of volts.

- **Probably the best-known application is the electric cigarette lighter: pressing the button causes a spring-loaded hammer to hit a piezoelectric crystal, and the high voltage produced ignites the gas as the current jumps over a small spark gap.**

- **A piezoelectric transformer is a type of AC voltage multiplier. Unlike a conventional transformer, which uses magnetic coupling between input and output, the piezoelectric transformer uses acoustic coupling. An input voltage is applied across a short length of a bar of piezoceramic material such as PZT, creating an alternating stress in the bar by the inverse piezoelectric effect and causing the whole bar to vibrate.**

b) Sensors

- **The principle of operation of a piezoelectric sensor is, that a physical dimension, transformed into a force, acts on two opposing faces of the sensing element.**

- **To detect sound, e.g. piezoelectric microphones (sound waves bend the piezoelectric material, creating a changing voltage) and piezoelectric pickups for electrically amplified guitars. A piezosensor attached to the body of an instrument is known as a contact microphone.**

- **Piezoelectric elements are also used in the generation of sonar waves. Piezoelectric microbalances are used as very sensitive chemical and biological sensors.**

- **Piezoelectric transducers are used in electronic drum pads to detect the impact of the drummer's sticks.**

- **Automotive engine management systems use a piezoelectric transducer to detect detonation, by sampling the vibrations of the engine block.**

c) Actuators

As very high voltages correspond to only tiny changes in the width of the crystal, this width can be changed with better-than-micrometer precision, making piezo crystals the most important tool for positioning objects with extreme accuracy.

- **Loudspeakers: Voltages are converted to mechanical movement of a piezoelectric polymer film.**

- **Atomic force microscopes and scanning tunneling microscopes employ converse piezoelectricity to keep the sensing needle close to the probe.**

- **Inkjet printers: on some high-end inkjet printers, piezoelectric crystals are used to control the flow of ink from the cartridge to the paper.**

- **Diesel engines: high-performance common rail diesel engines use piezoelectric fuel injectors, first developed by Siemens AG, instead of the more common solenoid valve devices.**

d) Piezoelectric motors

Types of piezoelectric motor include the well-known traveling-wave motor used for auto-focus in reflex cameras, inchworm motors for linear motion, and rectangular four-quadrant motors with high power density (2.5 watt/cm^3) and speed ranging from 10 nm/s to 800 mm/s. In most piezoelectric motors the piezoelectric crystal is excited by a sine wave signal at the resonant frequency of the motor. Using the resonance effect, a much lower voltage can be used to produce high vibration amplitude.

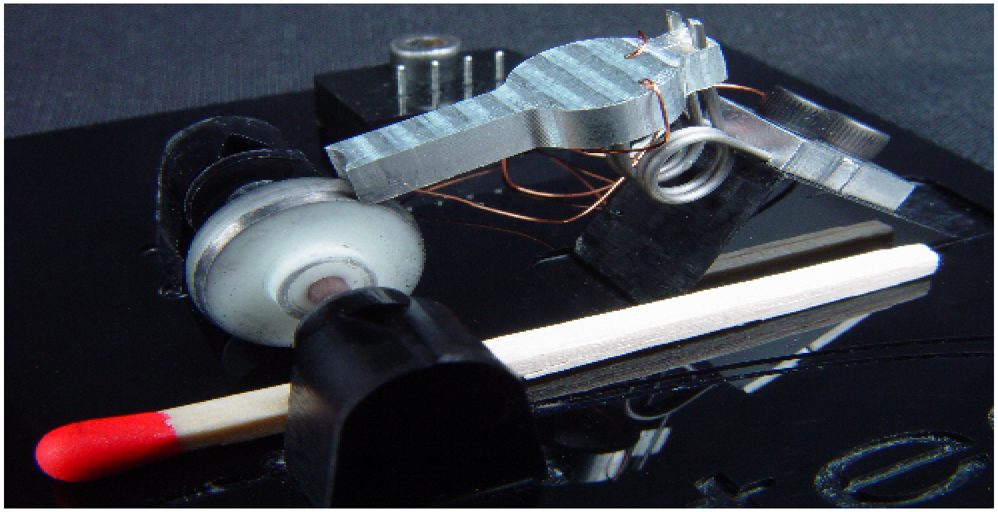


Figure 2: Piezoelectric motor

e) Ultrasonic transducers

Piezoelectric materials are used as ultrasonic transducers for imaging applications (eg medical imaging, industrial nondestructive testing, or NDT) and high power applications (e.g. medical treatment and industrial processing).

For imaging applications, the transducer can act as both a sensor and an actuator. Ultrasonic transducers can inject ultrasound waves into the body, receive the returned wave, and convert it to an electrical signal (a voltage). Most medical ultrasound transducers are piezoelectric.

Figure 3: Piezoelectric Ultrasonic Transducers

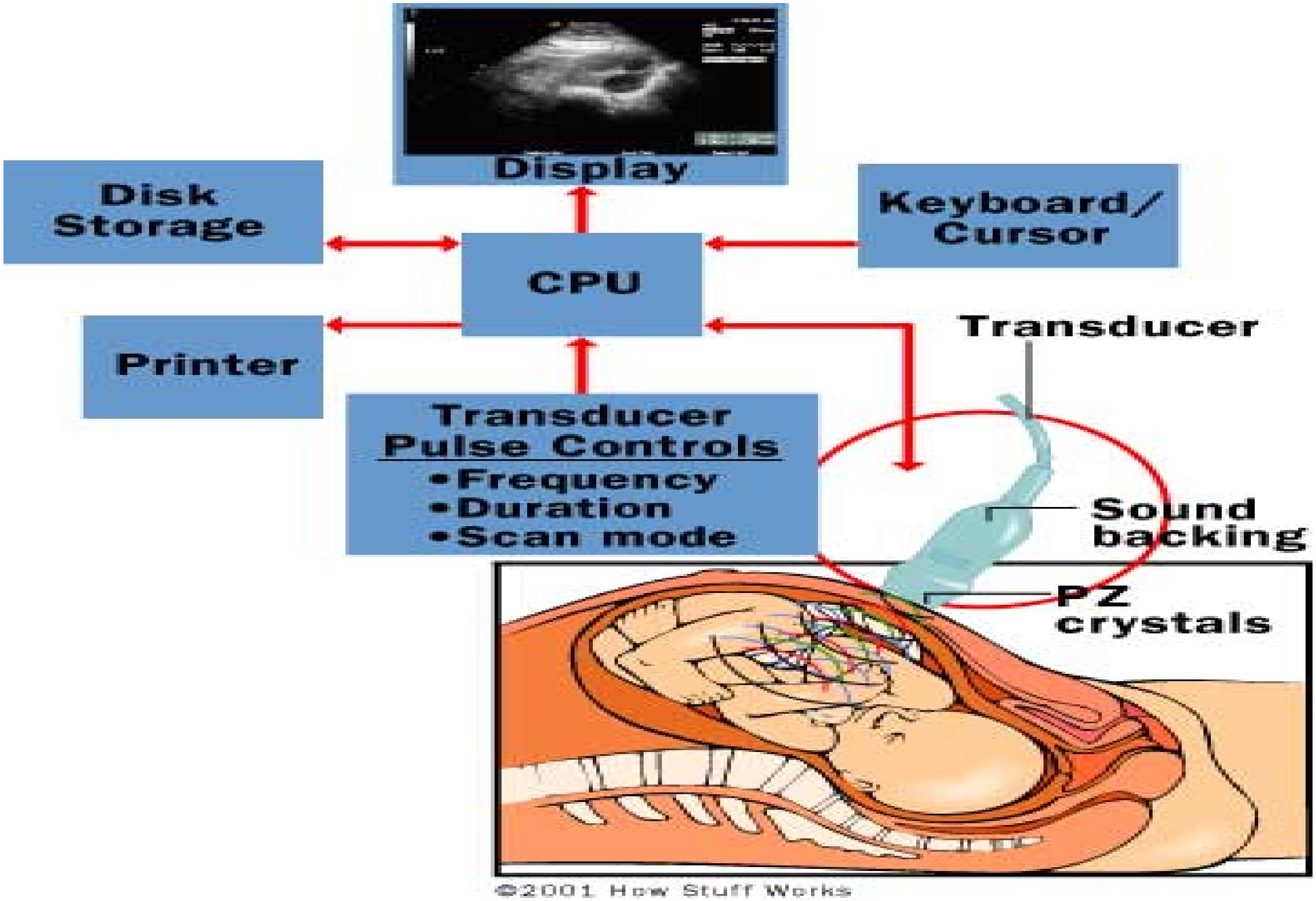


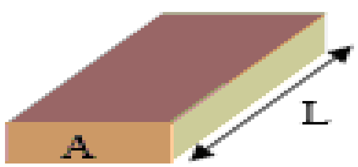
Figure 4: Ultrasonic imaging system

Piezoresistivity

The Piezoresistive Sensors

It's a kind of sensors made of monocrystalline silicon, consider as passive devices, it has come into wide use in recent years. It's manufactured with semiconductor technology. It uses the resistive principle. Peizoresistive materials have the property of changing their Resistance under physical pressure or mechanical work, so If a peizoresistive material is strained or deflected its internal resistance will change and stay changed until the material's original position is restored, in order to detect this change in resistance a power supply is necessary.

- Consider the resistance of a rectangular beam with resistivity ρ [Ω cm]:



$$R = \frac{\rho L}{A}$$

$$\ln R = \ln \rho + \ln L - \ln A$$

$$\frac{dR}{R} = \frac{d\rho}{\rho} + \frac{dL}{L} - \frac{dA}{A} = \underbrace{\frac{d\rho}{\rho}}_{\text{piezoresistive effect}} + \underbrace{\varepsilon(1+\nu)}_{\text{gauge effect}}$$

- Gauge factor: $GF = \frac{1}{\varepsilon}\frac{dR}{R} \longrightarrow R(\varepsilon) = R_0 + dR = R_0(1 + GF\,\varepsilon)$

The sensitivity of piezoresistive devices is characterized by the gauge factor. ν denotes the material dependent Poisson's ratio, Є and R denote the relative increase of length of the element and the resistance, respectively.

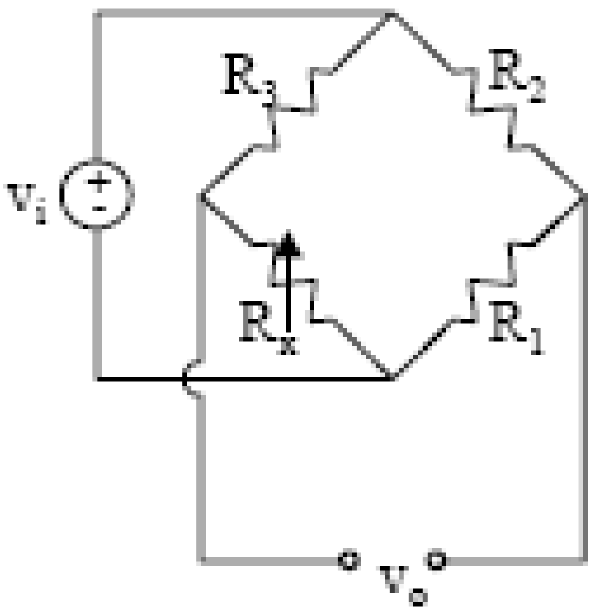
The piezoresistive effect of metal sensors is only due to the change of the sensor geometry resulting from applied mechanical stress.

The piezoresistive effect of semiconductor materials can be several magnitudes larger than the geometrical piezoresistive effect in metals and is present in materials like germanium, polycrystalline silicon, amorphous silicon, and single crystal silicon.

The resistivity of silicon changes not only due to the stress dependent change of geometry, but also due to the stress dependent resistivity of the material. This results in gauge factors two magnitudes larger than those observed in metals. The resistance of n-conducting silicon mainly changes due to a shift of the three different conducting valley pairs. The shifting causes a redistribution of the carriers between valleys with different motilities. This results in varying motilities dependent on the direction of current flow. A minor effect is due to the effective mass change related to changing shapes of the valleys. In p-conducting silicon the phenomena are more complex and also result in mass changes and hole transfer.

Peizoresistive component is typically arranged in a Wheatstone bridge circuit, whose output is a voltage proportional to the change in resistance.

- Wheatstone bridge
  - Good sensitivity
  - Temperature independent (to first order)
  - Simple implimentation:



$$v_o = v_i\left(\frac{R_x}{R_x + R_3} - \frac{R_1}{R_1 + R_2}\right)$$

$@v_o = 0:$

$$\frac{R_x / R_3}{R_x / R_3 + 1} = \frac{R_1 / R_2}{R_1 / R_2 + 1} \Rightarrow \frac{R_x}{R_3} = \frac{R_1}{R_2}$$

History

The change of resistance of metal devices due to an applied mechanical load was first discovered in 1856 by Lord Kelvin. With single crystal silicon becoming the material of choice for the design of analog and digital circuits, the large piezoresistive effect in silicon and germanium was first discovered in 1954 (Smith 1954).

Piezoresistive silicon devices

Piezoresistors are resistors made from a piezoresistive material and are usually used for measurement of mechanical stress. They are the simplest form of piezoresistive devices.

The piezoresistive effect of semiconductors has been used for sensor devices employing all kinds of semiconductor materials such as germanium, polycrystalline silicon, amorphous silicon, and single crystal silicon. Due to the fact that silicon is today the material of choice for integrated digital and analog circuits the use of piezoresistive silicon devices has been of great interest. It enables the easy integration of stress sensors with Bipolar and CMOS circuits.

This has enabled a wide range of products using the piezoresisitve effect. Many commercial devices such pressure sensors and acceleration sensors employ the piezoresistive effect in silicon. But due to its magnitude the piezoresistive effect in silicon has also attracted the attention of research and development for all other devices using single crystal silicon. Semiconductor Hall sensors, for example, were capable of achieving their

current precision only after employing methods which eliminate signal contributions due the applied mechanical stress.

Piezoresistors can be fabricated using wide variety of piezoresistive materials. The simplest form of piezoresistive silicon sensors are diffused resistors. Piezoresistors consist of a simple two contact diffused n- or p-wells within a p- or n-substrate. As the typical square resistances of these devices are in the range of several hundred ohms, additional p+ or n+ diffusions are necessary to facilitate ohmic contacts to the device.

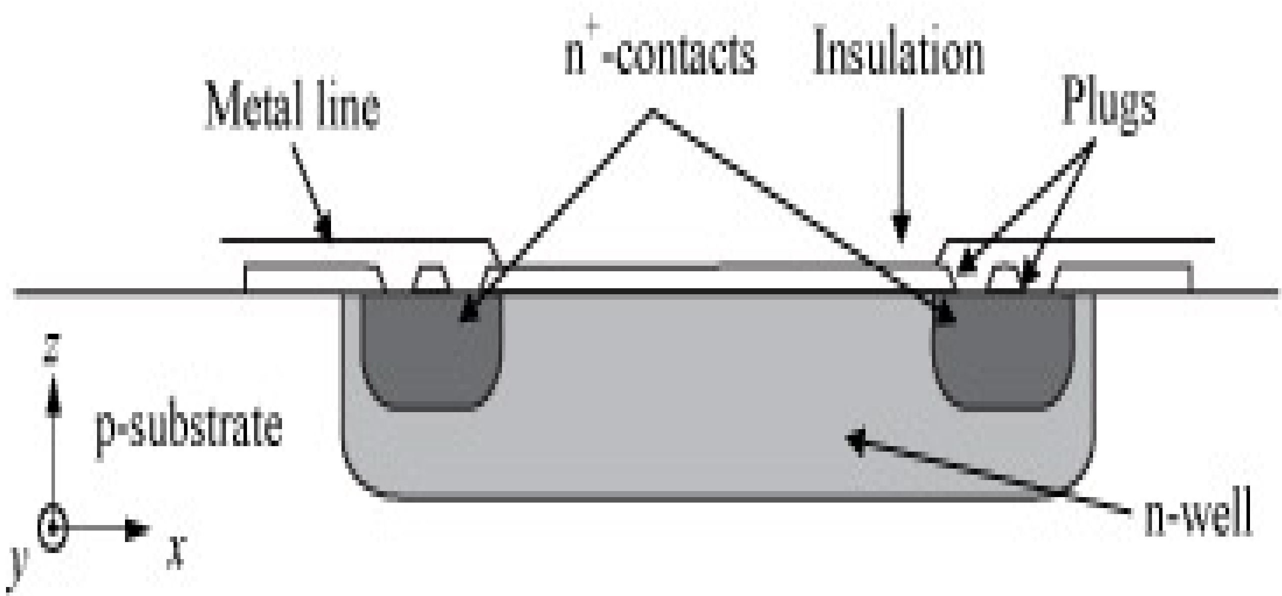


Figure 5: Schematic cross-section of the basic elements of a silicon n-well piezoresistor

Applications

There are different types of peizoresistive like pressure and temperature sensors(there 're used in thermostats which is in different kind of machines like car's motor ,washing machine ,fans of motors and refrigerators. Properties:

-Small size

-Good linearity over wide dynamic range

-Moderately high pressure sensitivity

-Relative freedom from hysteresis and creep

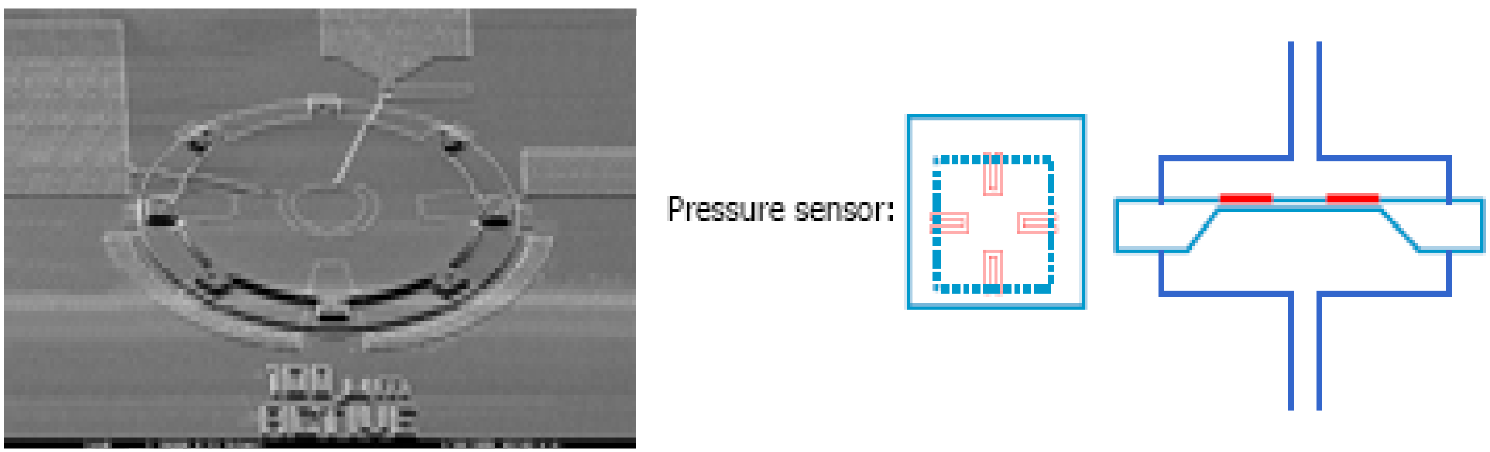
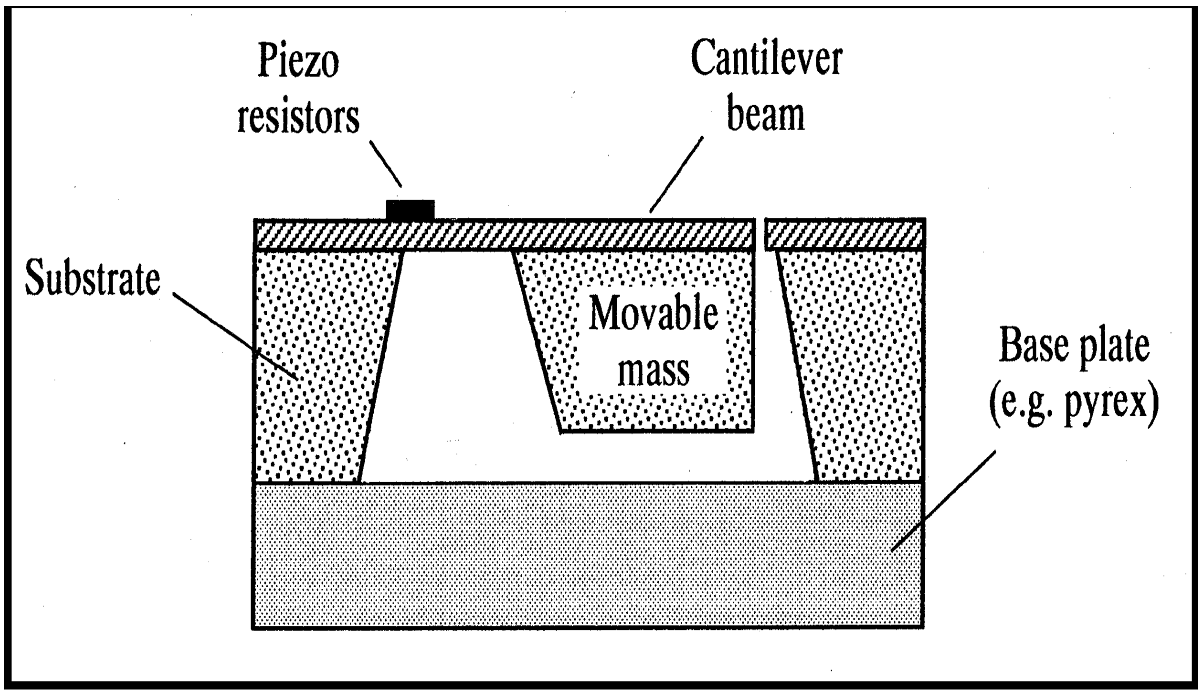


Figure 6: Piezoresistive pressure sensor

Most piezoresistive accelerometer designs use the sensor's pendulous arm, connected to the proof mass, as a strain gauge. Peizoresistive accelerometers are attractive for most applications due to low cost, Easy implementation and simple detection electronics.

The disadvantages of Peizoresistive accelerometers are the large temperature sensitivity, small overall sensitivity.



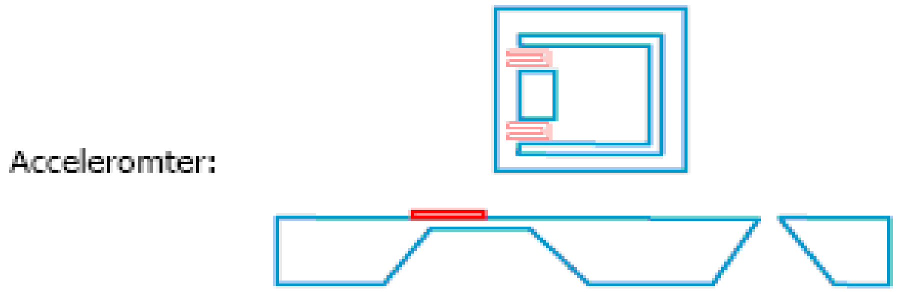


Figure 7: Piezoresistive accelerometer

Also piezoresistors can be used as force feedback microgripper and a cell force sensor.

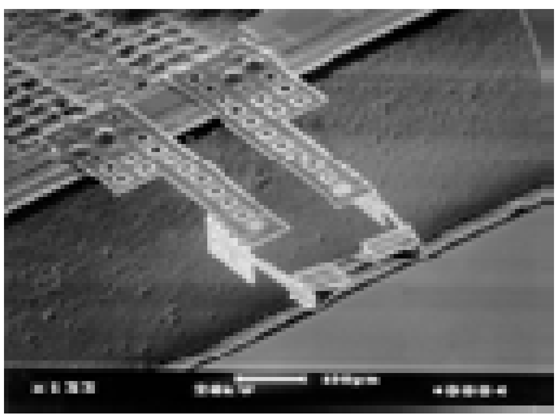


Figure 8: Cell force sensor

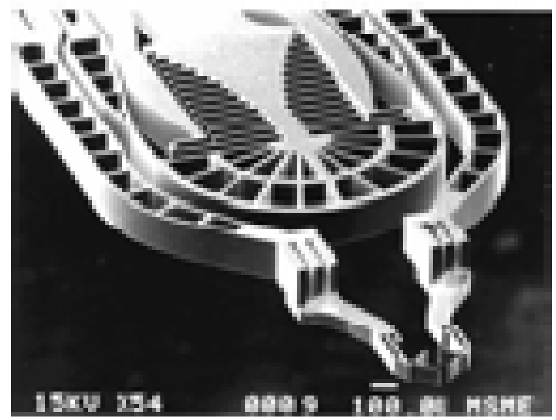


Figure 9: Force feedback microgripper

Piezoresistors also can be used as a flow sensors as shown in figure 6. Here, cantilever deflection is translated into a voltage signal via the Wheatstone bridge. Voltage change is interpreted as flow rate. The sensor can sense direction and magnitude of flow.

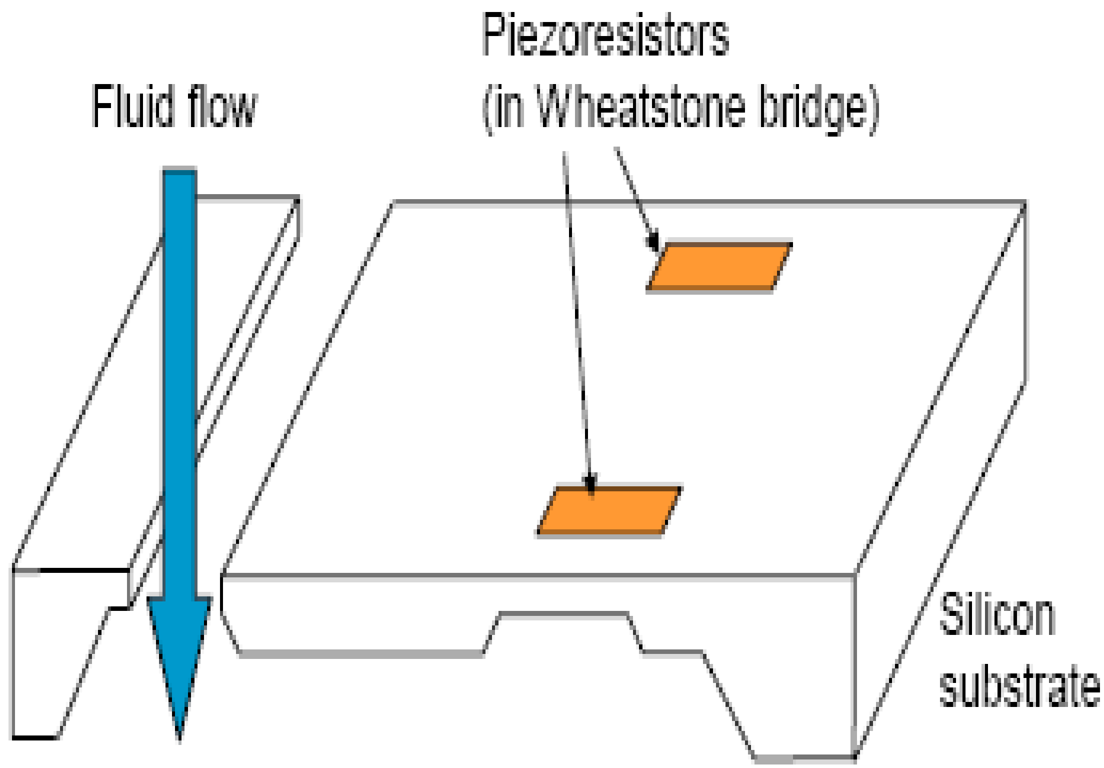


Figure 10: Piezoresistive flow sensing

Advantages:

High sensitivity, >10 mV/V

Good linearity at constant temperature

Simple fabrication

Simple interface circuits: measure change in R using a simple Wheatstone bridge topology

Disadvantages:

Temperature sensitive

High thermal noise