Semiconductor Sensors:

Ch7: Piezoresistive Sensors

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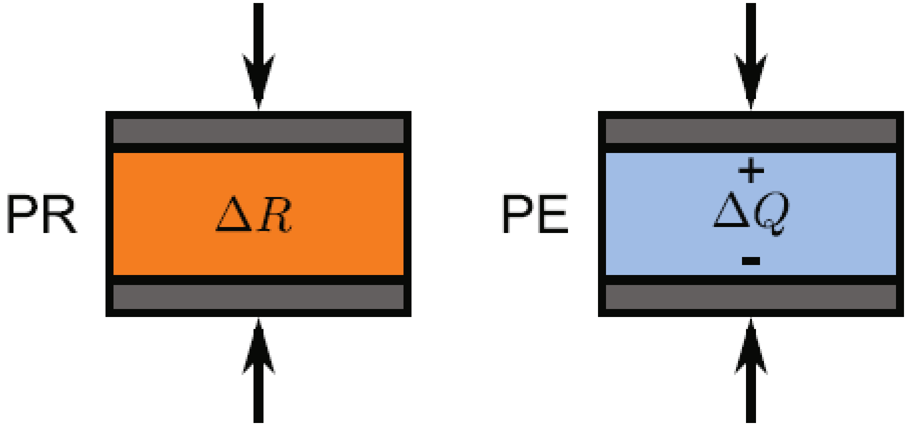
اثر پیزورزیست



Mechanical stress induces a resistance change in piezoresistive (PR) materials and charge polarization in piezoelectric (PE) materials.

J. C. Doll and B.L. Pruitt. *Piezoresistor design and applications*. Springer, 2016.

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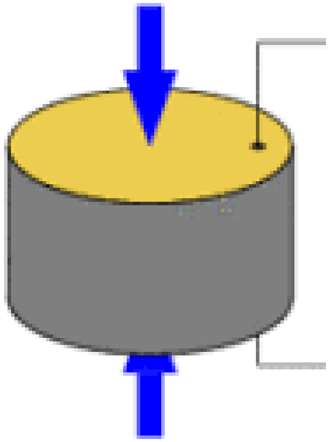
The fundamental principle of piezoresistive sensors comes from Equation:

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

Taking natural logarithm on both sides yields:

$$\ln(R) = \ln(\rho) + \ln(l) - \ln(A)$$



The differential of the aforementioned equation becomes:

$$\frac{dR}{R} = \frac{d\rho}{\rho} + \frac{dl}{l} - \frac{dA}{A}$$

Let $A = \pi D^2/4$, where D is the diameter of a wire:

$$\ln(A) = \ln(\pi/4) + 2\ln(D)$$

The differential of this equation results:

$$\frac{dA}{A} = 2\frac{dD}{D}$$

Ebook: W. Y. Du "*Resistive, capacitive, inductive, and magnetic sensor technologies*", CRC Press, 2014.

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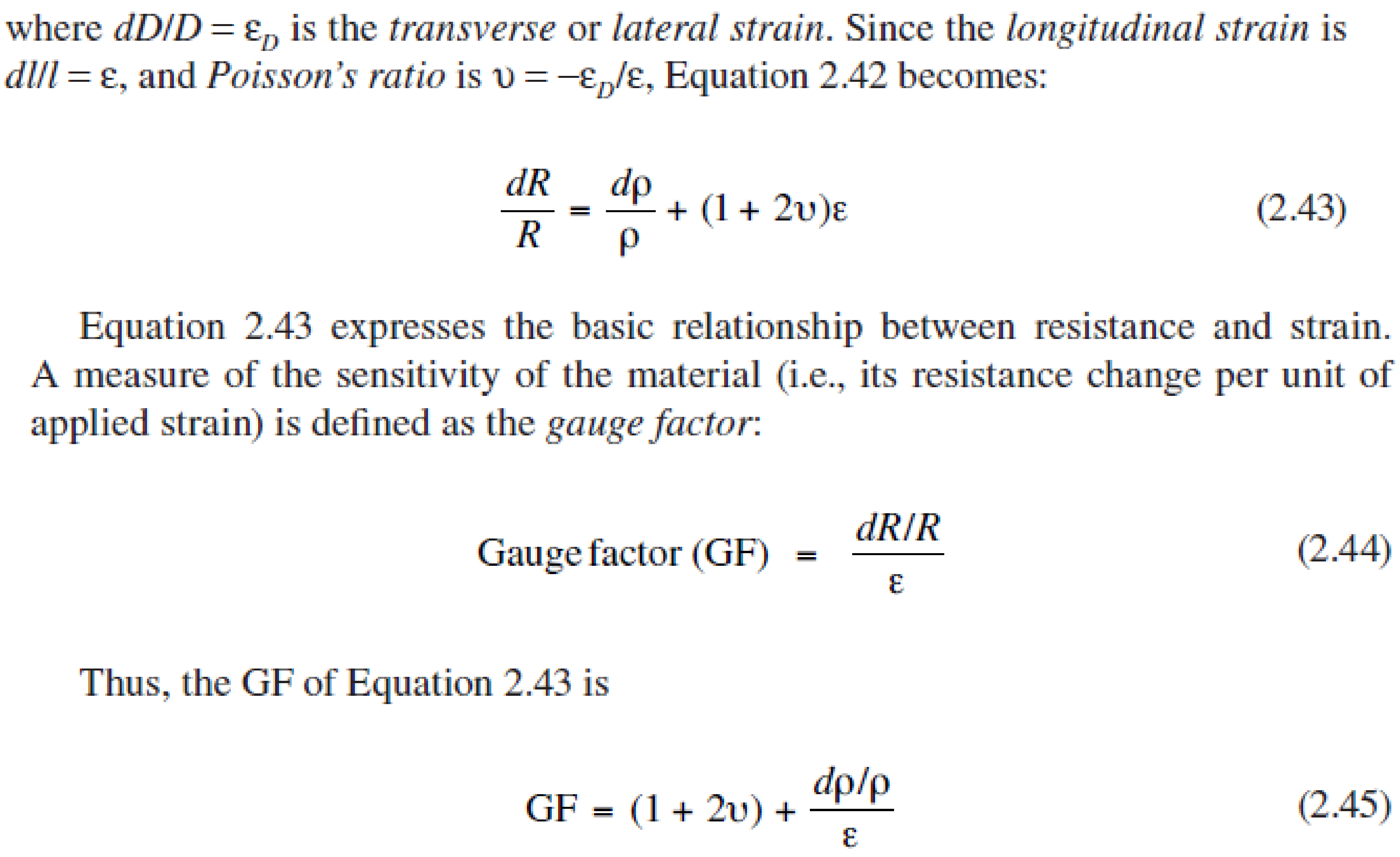

where $dD/D = \varepsilon_D$ is the *transverse* or *lateral strain*. Since the *longitudinal strain* is $dl/l = \varepsilon$, and *Poisson's ratio* is $\upsilon = -\varepsilon_D/\varepsilon$, Equation 2.42 becomes:

$$\frac{dR}{R} = \frac{d\rho}{\rho} + (1 + 2\upsilon)\varepsilon \qquad (2.43)$$

Equation 2.43 expresses the basic relationship between resistance and strain. A measure of the sensitivity of the material (i.e., its resistance change per unit of applied strain) is defined as the *gauge factor*:

$$\text{Gauge factor (GF)} = \frac{dR/R}{\varepsilon} \qquad (2.44)$$

Thus, the GF of Equation 2.43 is

$$\text{GF} = (1 + 2\upsilon) + \frac{d\rho/\rho}{\varepsilon} \qquad (2.45)$$

Ebook: W. Y. Du "*Resistive, capacitive, inductive, and magnetic sensor technologies*", CRC Press, 2014.

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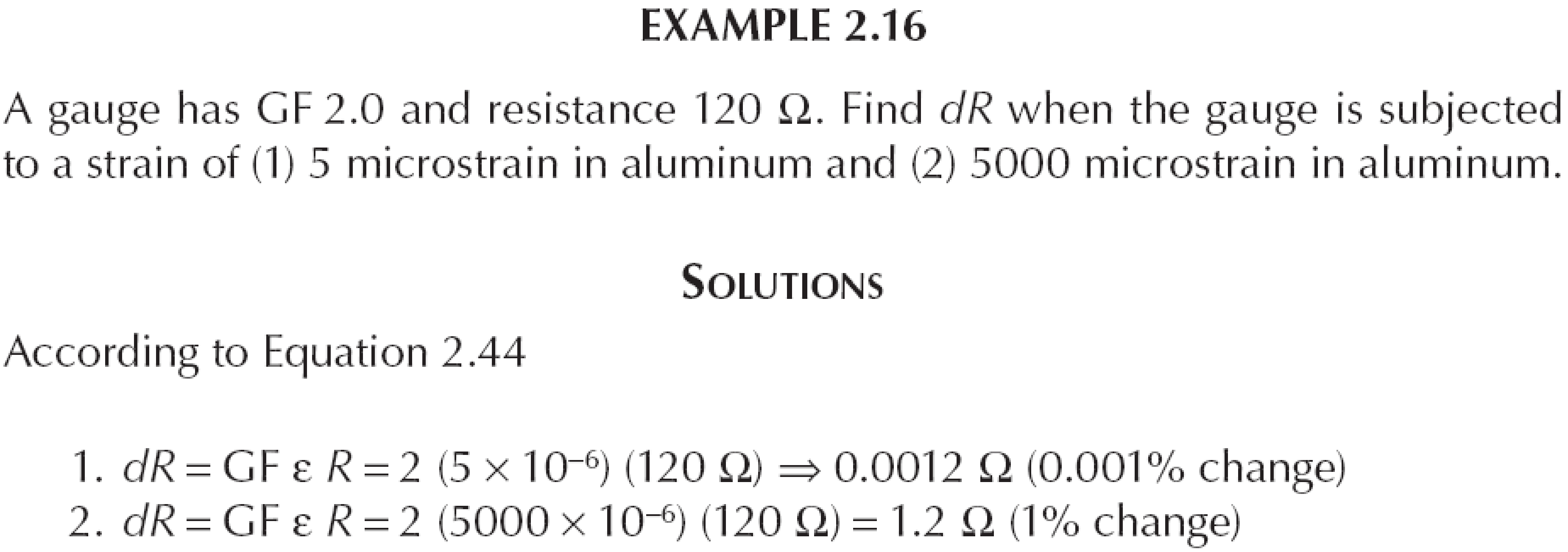


EXAMPLE 2.16

A gauge has GF 2.0 and resistance 120 Ω. Find dR when the gauge is subjected to a strain of (1) 5 microstrain in aluminum and (2) 5000 microstrain in aluminum.

SOLUTIONS

According to Equation 2.44

1. $dR = \text{GF}\ \varepsilon\ R = 2\ (5 \times 10^{-6})\ (120\ \Omega) \Rightarrow 0.0012\ \Omega$ (0.001% change)
2. $dR = \text{GF}\ \varepsilon\ R = 2\ (5000 \times 10^{-6})\ (120\ \Omega) = 1.2\ \Omega$ (1% change)

Ebook: W. Y. Du "*Resistive, capacitive, inductive, and magnetic sensor technologies*", CRC Press, 2014.

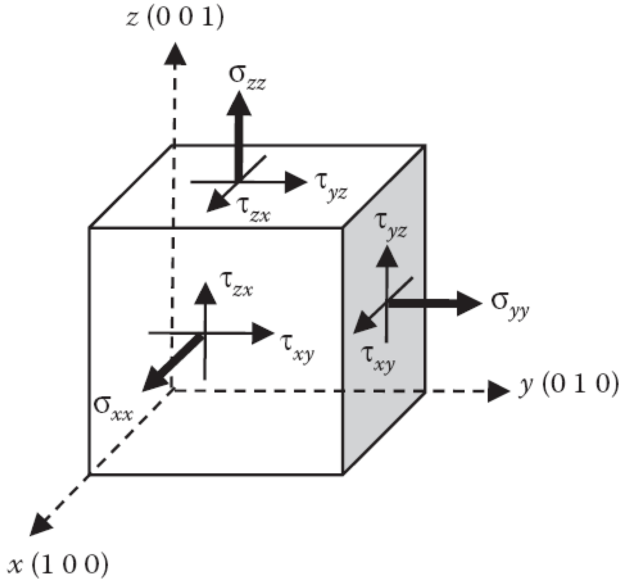
اثر پیزورزیست در نیمه رسانا ها و علت آن

Piezoresistive effect in silicon and germanium was discovered by Charles Smith in 1954. He found that both *p*-type and *n*-type silicon and germanium exhibited much greater piezoresistive effect than metals.

Piezoresistivity of silicon arises from the deformation of the energy bands as a result of applied stress. In turn, the deformed bands affect the effective mass and the mobility of electrons and holes, hence modifying resistivity or conductivity.

اثر پیزورزیست

To understand how the resistance change relates to the applied stress, consider an infinitesimally small cubic piezoresistive crystal element with normal stresses σ_{xx}, σ_{yy}, and σ_{zz} along the cubic crystal axes x, y, and z, respectively, and three shear stresses τ_{yz}, τ_{zx}, and τ_{xy}, as indicated in Figure 2.24. The piezoresistive effect in this case can be described by relating the resistance change ΔR to each of the six stress components using a matrix of 36 coefficients, π_{ij}, expressed in Pa^{-1}, as shown in Equation 2.46.



Definition of the normal stresses σ_i and shear stresses τ_i ($i = 1, 2, 3$).

Ebook: W. Y. Du "*Resistive, capacitive, inductive, and magnetic sensor technologies*", CRC Press, 2014.

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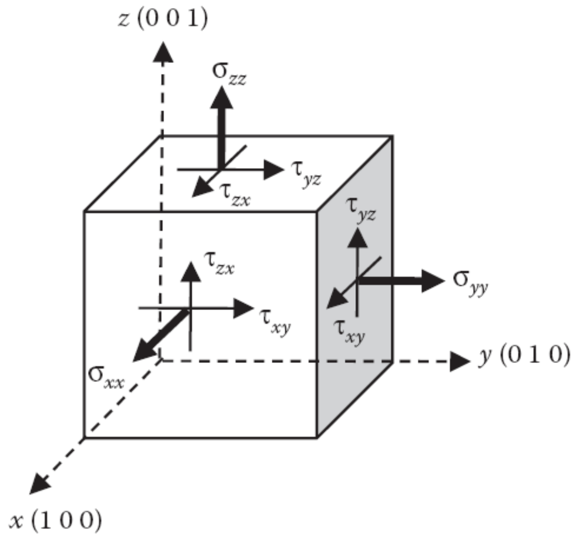
$$\frac{1}{R}\underbrace{\begin{bmatrix}\Delta R_{xx}\\ \Delta R_{yy}\\ \Delta R_{zz}\\ \Delta R_{yz}\\ \Delta R_{zx}\\ \Delta R_{xy}\end{bmatrix}}_{\Delta\vec{R}} = \underbrace{\begin{bmatrix}\pi_{11} & \pi_{12} & \pi_{13} & \pi_{14} & \pi_{15} & \pi_{16}\\ \pi_{21} & \pi_{22} & \pi_{23} & \pi_{24} & \pi_{25} & \pi_{26}\\ \pi_{31} & \pi_{32} & \pi_{33} & \pi_{34} & \pi_{35} & \pi_{36}\\ \pi_{41} & \pi_{42} & \pi_{43} & \pi_{44} & \pi_{45} & \pi_{46}\\ \pi_{51} & \pi_{52} & \pi_{53} & \pi_{54} & \pi_{55} & \pi_{56}\\ \pi_{61} & \pi_{62} & \pi_{63} & \pi_{64} & \pi_{65} & \pi_{66}\end{bmatrix}}_{\Pi}\underbrace{\begin{bmatrix}\sigma_{xx}\\ \sigma_{yy}\\ \sigma_{zz}\\ \tau_{yz}\\ \tau_{zx}\\ \tau_{xy}\end{bmatrix}}_{\vec{\sigma}} \qquad (2.46)$$



where the vector $\Delta\vec{R}$ represents the change in resistance with corresponding stress components, R is the original resistance, and Π is a 6 × 6 *piezoresistive coefficient matrix*. If the coordinate axes coincide with the crystal axes, a cubic crystal has three independent, nonvanishing elastic components, π_{11}, π_{12}, and π_{44}, that is

$$\pi_{11} = \pi_{22} = \pi_{33}$$

$$\pi_{12} = \pi_{21} = \pi_{13} = \pi_{31} = \pi_{23} = \pi_{32}$$

$$\pi_{44} = \pi_{55} = \pi_{66}$$

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Thus, the Π matrix becomes

$$\Pi = \begin{bmatrix} \pi_{11} & \pi_{12} & \pi_{12} & 0 & 0 & 0 \\ \pi_{12} & \pi_{11} & \pi_{12} & 0 & 0 & 0 \\ \pi_{12} & \pi_{12} & \pi_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & \pi_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & \pi_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & \pi_{44} \end{bmatrix}$$

$$\Delta R_1/R = \pi_{11}\sigma_1 + \pi_{12}(\sigma_2 + \sigma_3) \qquad \Delta R_4/R = \pi_{44}\tau_1$$

$$\Delta R_2/R = \pi_{11}\sigma_2 + \pi_{12}(\sigma_1 + \sigma_3) \qquad \Delta R_5/R = \pi_{44}\tau_2$$

$$\Delta R_3/R = \pi_{11}\sigma_3 + \pi_{12}(\sigma_1 + \sigma_2) \qquad \Delta R_6/R = \pi_{44}\tau_3$$

using 1—xx, 2—yy, 3—zz, 4—yz, 5—zx, and 6—xy

Ebook: W. Y. Du "*Resistive, capacitive, inductive, and magnetic sensor technologies*", CRC Press, 2014.

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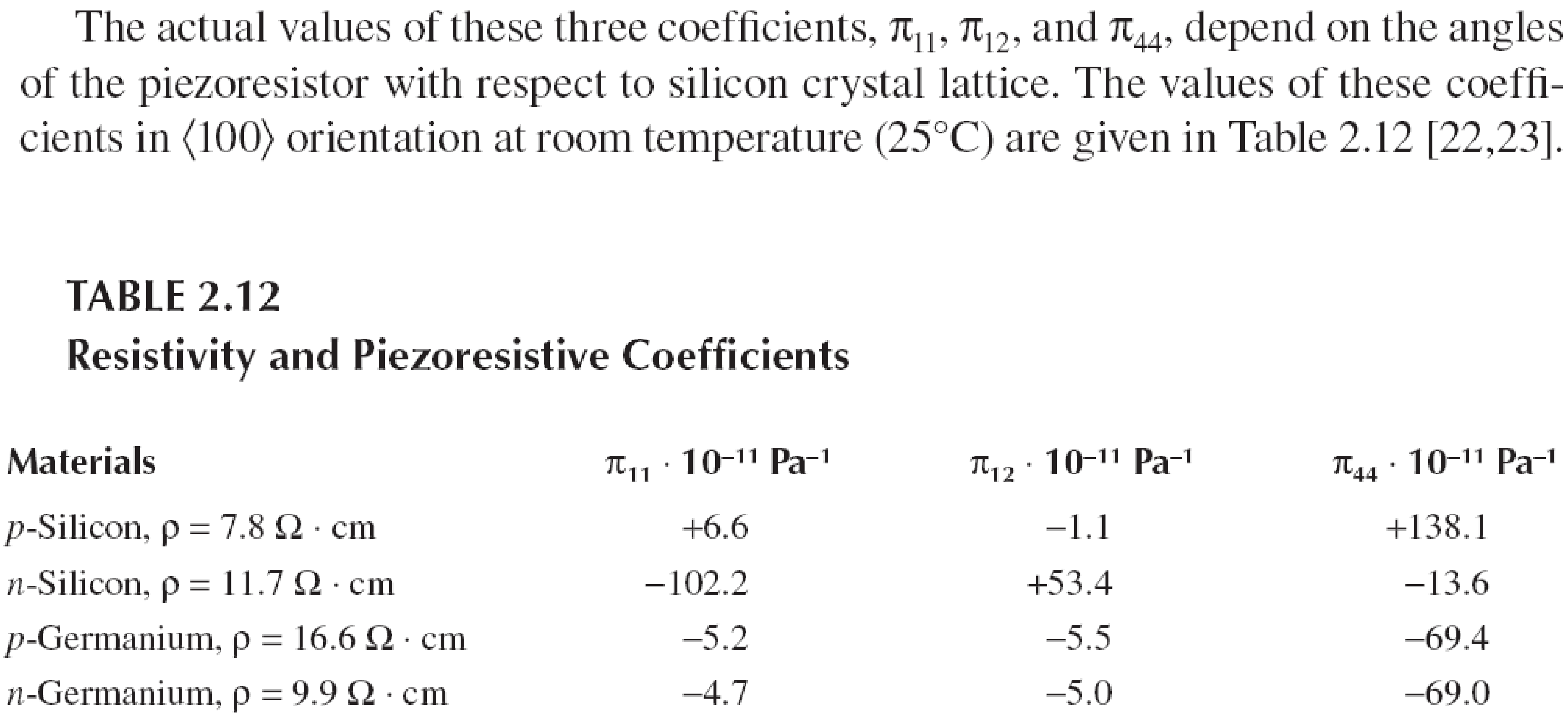

The actual values of these three coefficients, π_{11}, π_{12}, and π_{44}, depend on the angles of the piezoresistor with respect to silicon crystal lattice. The values of these coefficients in ⟨100⟩ orientation at room temperature (25°C) are given in Table 2.12 [22,23].

TABLE 2.12
Resistivity and Piezoresistive Coefficients

Materials	$\pi_{11} \cdot 10^{-11}$ Pa^{-1}	$\pi_{12} \cdot 10^{-11}$ Pa^{-1}	$\pi_{44} \cdot 10^{-11}$ Pa^{-1}
p-Silicon, $\rho = 7.8\ \Omega \cdot$ cm	+6.6	−1.1	+138.1
n-Silicon, $\rho = 11.7\ \Omega \cdot$ cm	−102.2	+53.4	−13.6
p-Germanium, $\rho = 16.6\ \Omega \cdot$ cm	−5.2	−5.5	−69.4
n-Germanium, $\rho = 9.9\ \Omega \cdot$ cm	−4.7	−5.0	−69.0

Ebook: W. Y. Du "*Resistive, capacitive, inductive, and magnetic sensor technologies*", CRC Press, 2014.

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In practical applications, a thin strip of silicon is commonly used to make a strain gauge sensor, instead of a three-dimensional cube. In this case, change in resistance versus in-plane stresses in the longitudinal (parallel to the current) direction and transverse (perpendicular to the current) direction can be expressed as

$$\frac{\Delta R}{R} = \pi_L \sigma_L + \pi_T \sigma_T \tag{2.48}$$

where ΔR and R are the change in resistance and the original resistance, respectively; σ_L and σ_T are the longitudinal and transverse stress, respectively; π_L and π_T are the piezoresistive coefficient along the longitudinal and transverse direction, respectively.

Ebook: W. Y. Du "*Resistive, capacitive, inductive, and magnetic sensor technologies*", CRC Press, 2014.

EXAMPLE 2.17

A pressure sensor die contains four identical *p*-type piezoresistors (Figure 2.25). Resistors *A* and *C* are subjected to the longitudinal stress σ_L, and Resistors *B* and *D* are subjected to the transverse stress component σ_T. Assume that the square-shaped diaphragm is under uniform pressure loading at the top surface, $\sigma_L = \sigma_T = 186.8$ MPa, $\pi_L = \pi_T = 2.762 \times 10^{-11}\ \mathrm{Pa}^{-1}$. Estimate $\Delta R/R$.

SOLUTION

Since the square diaphragm is subjected to a uniform pressure load at the top surface, the bending moments are normal to all piezoresistors and are equal in magnitudes. Thus, for each resistor

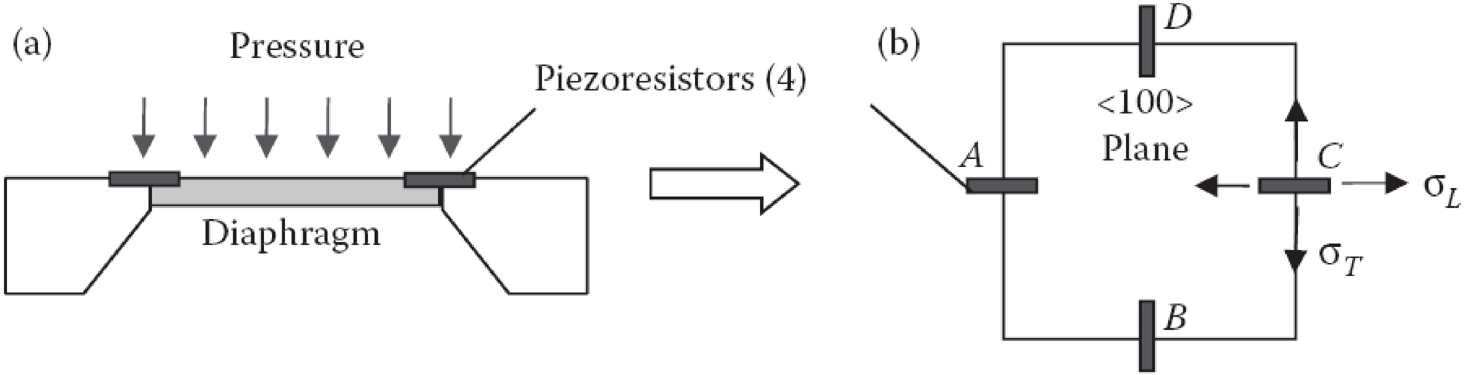

FIGURE 2.25 A semiconductor pressure sensor die: (a) side view; (b) top view.

$$\frac{\Delta R}{R} = \pi_L\sigma_L + \pi_T\sigma_T = 2 \times (2.762 \times 10^{-11}\ \mathrm{Pa}^{-1})(186.8 \times 10^{6}\ \mathrm{Pa}) = 0.01032 \text{ or } 1.032\%$$

Ebook: W. Y. Du "*Resistive, capacitive, inductive, and magnetic sensor technologies*", CRC Press, 2014.

اپارامترهای مهم پیزورزیستورها

The characteristics of a strain gauge are mainly defined by:

- Gauge dimensions and shape,
- Resistance,
- Gauge factor (Strain sensitivity),
- Temperature coefficient,
- Resistivity,
- Thermal stability.

Ebook: W. Y. Du ”*Resistive, capacitive, inductive, and magnetic sensor technologies*”, CRC Press, 2014.

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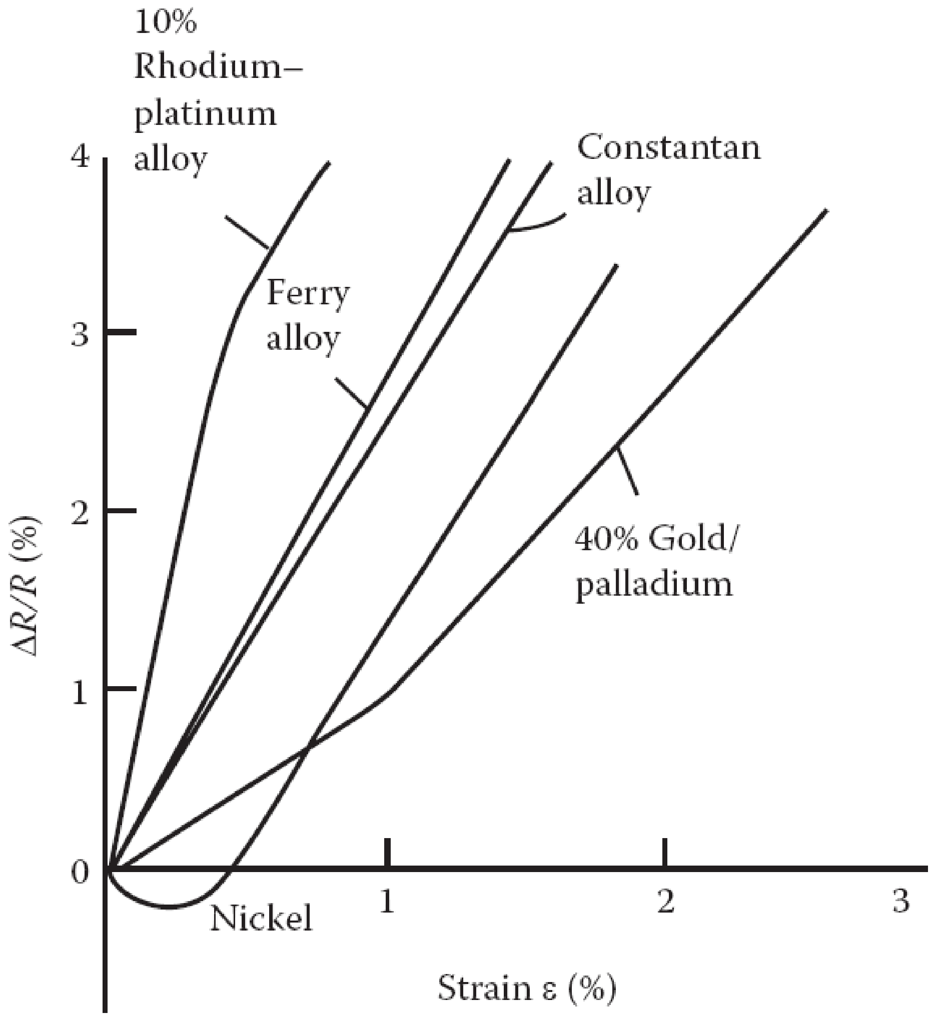

GF plots for various strain gauge element materials

Ebook: W. Y. Du "*Resistive, capacitive, inductive, and magnetic sensor technologies*", CRC Press, 2014.

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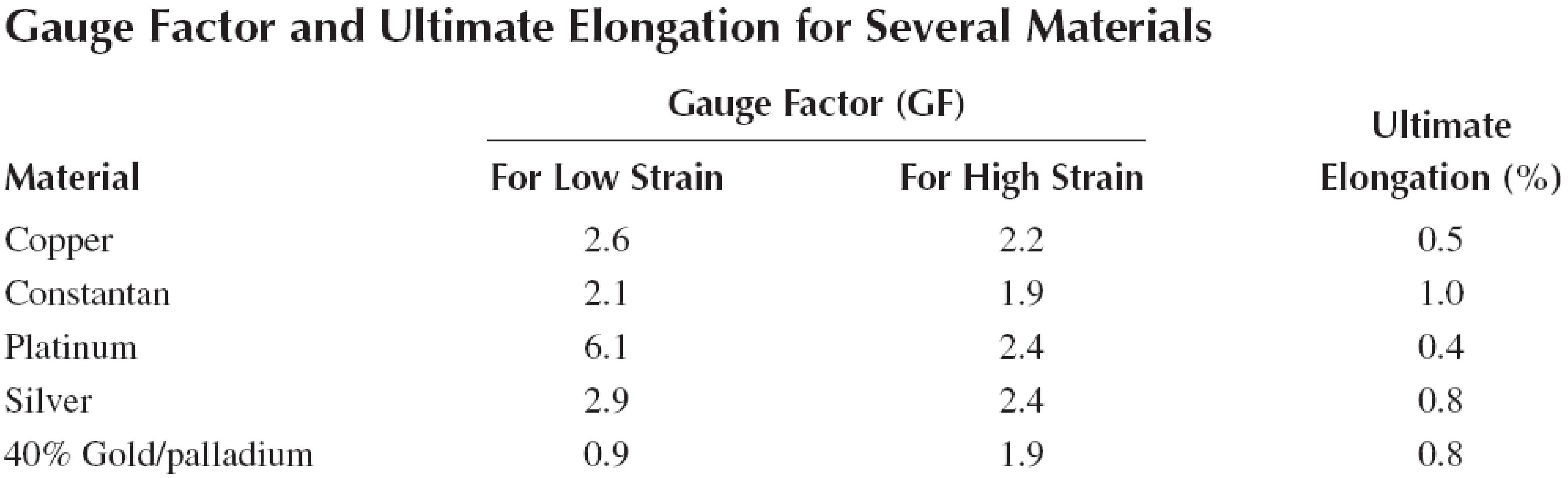
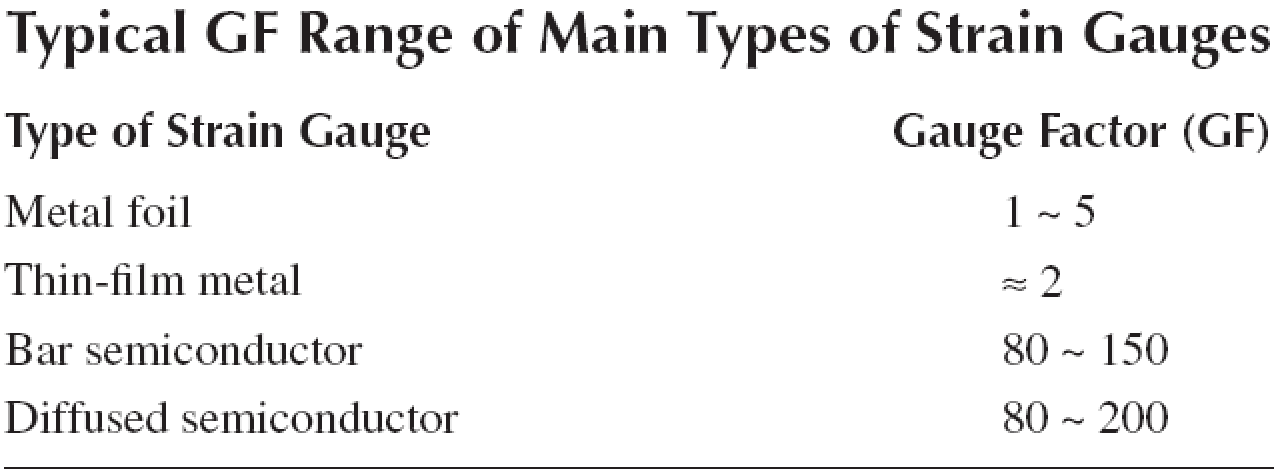


Gauge Factor and Ultimate Elongation for Several Materials

Material	Gauge Factor (GF)		Ultimate Elongation (%)
	For Low Strain	For High Strain	
Copper	2.6	2.2	0.5
Constantan	2.1	1.9	1.0
Platinum	6.1	2.4	0.4
Silver	2.9	2.4	0.8
40% Gold/palladium	0.9	1.9	0.8



Typical GF Range of Main Types of Strain Gauges

Type of Strain Gauge	Gauge Factor (GF)
Metal foil	1 ~ 5
Thin-film metal	≈ 2
Bar semiconductor	80 ~ 150
Diffused semiconductor	80 ~ 200

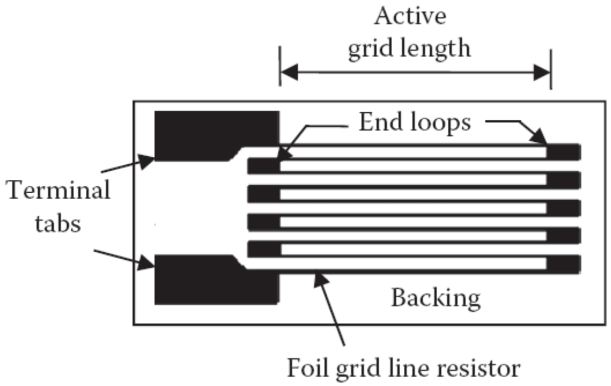
Ebook: W. Y. Du "*Resistive, capacitive, inductive, and magnetic sensor technologies*", CRC Press, 2014.

طراحی حسگر پیزو رزیستیو

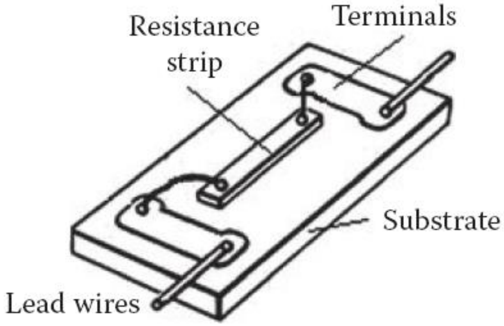
انواع گیج فشاری:

Types of strain gauges include:

- Wire strain gauges,
- Metal foil strain gauges,
- Single-crystal semiconductor strain gauges,
- Thin-film strain gauges.



Metal foil strain gauge construction.



A single-crystal semiconductor strain gauge. (United States Patent

طراحی حسگر پیزو رزیستیو

گیج فشاری- نوع لایه نازک:

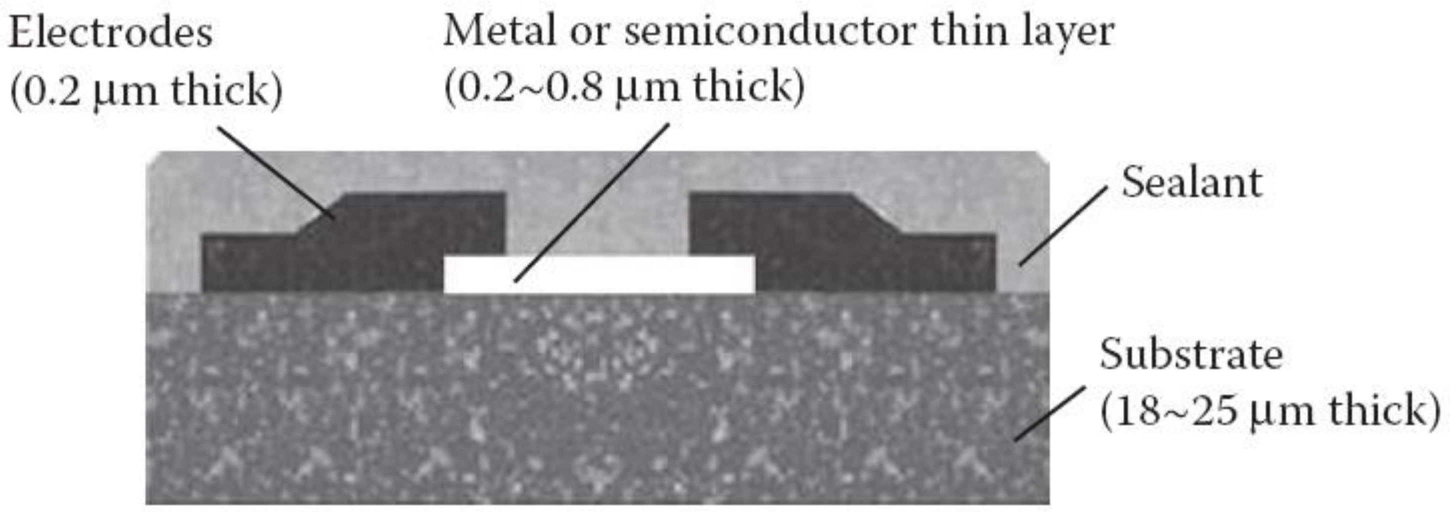
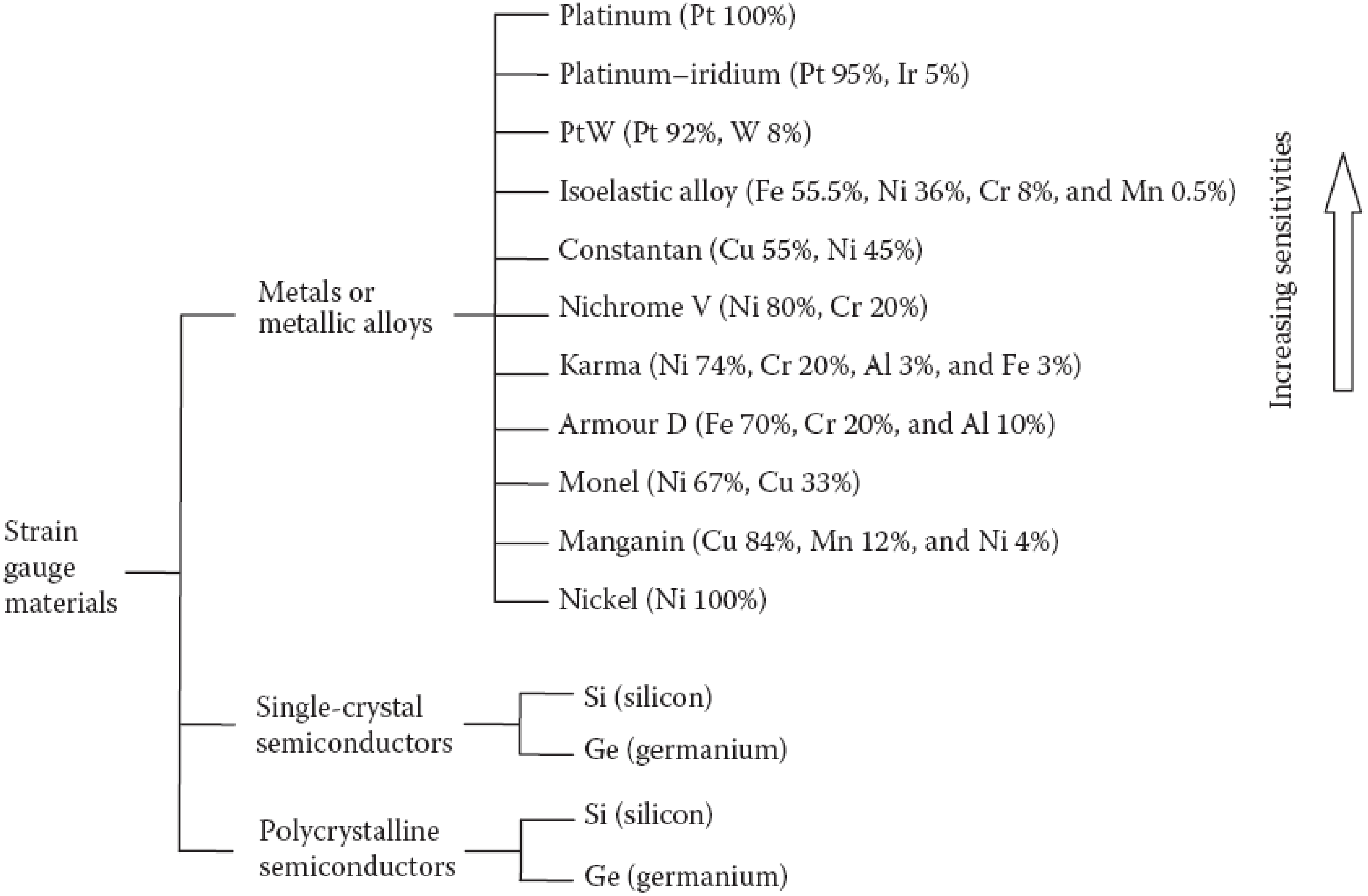


FIGURE 2.31 Structure of a thin-film strain gauge.

Ebook: W. Y. Du "*Resistive, capacitive, inductive, and magnetic sensor technologies*", CRC Press, 2014.

طراحی حسگر پیزو رزیستیو - مواد



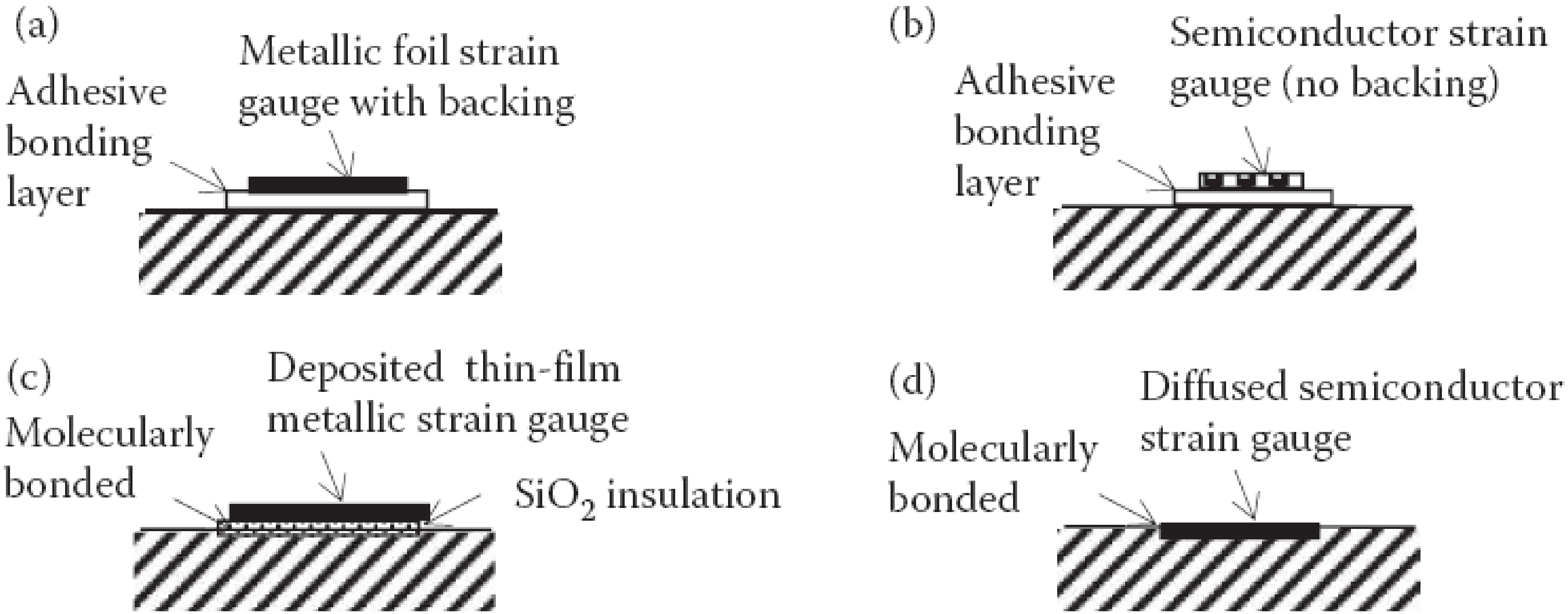
- Strain gauge materials
  - Metals or metallic alloys
    - Platinum (Pt 100%)
    - Platinum–iridium (Pt 95%, Ir 5%)
    - PtW (Pt 92%, W 8%)
    - Isoelastic alloy (Fe 55.5%, Ni 36%, Cr 8%, and Mn 0.5%)
    - Constantan (Cu 55%, Ni 45%)
    - Nichrome V (Ni 80%, Cr 20%)
    - Karma (Ni 74%, Cr 20%, Al 3%, and Fe 3%)
    - Armour D (Fe 70%, Cr 20%, and Al 10%)
    - Monel (Ni 67%, Cu 33%)
    - Manganin (Cu 84%, Mn 12%, and Ni 4%)
    - Nickel (Ni 100%)
  - Single-crystal semiconductors
    - Si (silicon)
    - Ge (germanium)
  - Polycrystalline semiconductors
    - Si (silicon)
    - Ge (germanium)

Ebook: W. Y. Du "*Resistive, capacitive, inductive, and magnetic sensor technologies*", CRC Press, 2014.

طراحی حسگر پیزو رزیستیو - اتصال

Bonding methods for strain gauge:

(a) adhesive bonding with backing,
(b) adhesive bonding without backing,
(c) deposited molecular bonding,
(d) diffused molecular bonding.



Ebook: W. Y. Du "*Resistive, capacitive, inductive, and magnetic sensor technologies*", CRC Press, 2014.

کاربرد حسگر پیزو رزیستیو

Piezoresistive strain gauges are applied in measuring acceleration, force, torque, pressure, and vibration.

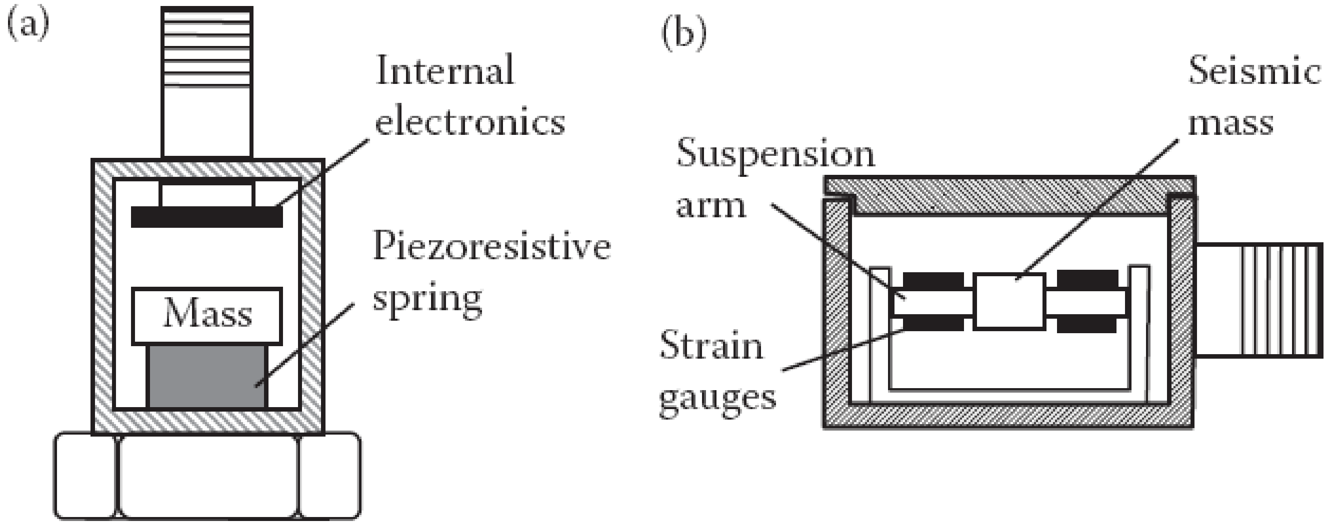


FIGURE 2.36 (a) Piezoresistive spring type accelerometer; (b) suspension arm type

Ebook: W. Y. Du "*Resistive, capacitive, inductive, and magnetic sensor technologies*", CRC Press, 2014.

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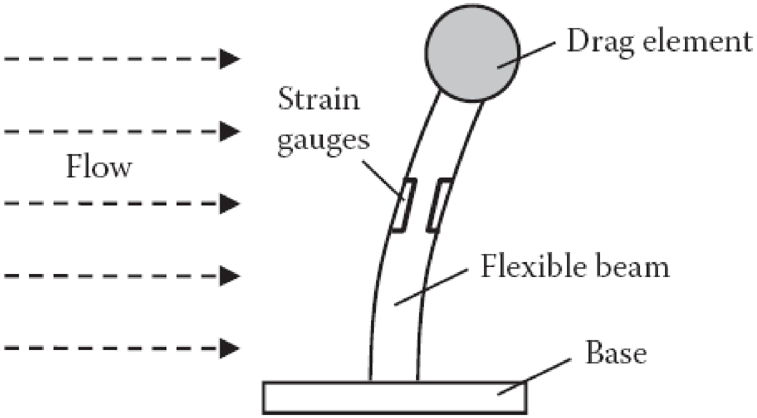
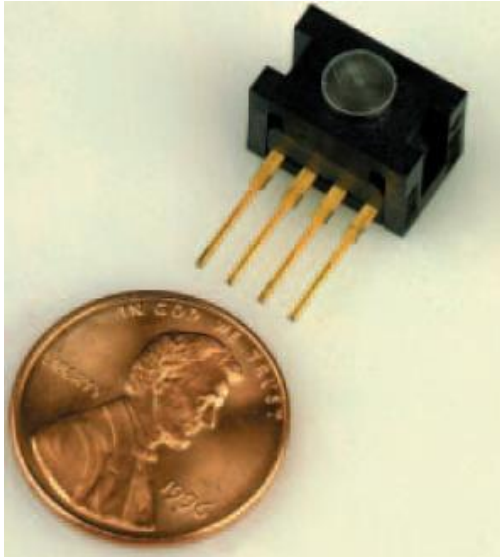


A piezoresistive flow rate sensor.

TABLE 2.18

Specifications of LPM 560 Micro Force Sensor

Load range: 0–1500 grams
Hysteresis: 45–180 grams
Temperature range: −40 to 185°F
Bridge resistance: 5 kΩ
Linearity: 22.5–25 grams
Repeatability: 30–120 grams
Output: 290–430 mV/FS
Excitation voltage: 10 VDC



Ebook: W. Y. Du "*Resistive, capacitive, inductive, and magnetic sensor technologies*", CRC Press, 2014.

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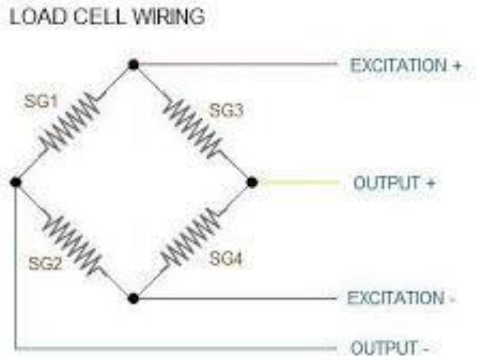
انواع نیروسنج Load cell



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