PIEZORESISTIVE DEVICES

Piezoresistive devices are devices whose functioning principle is based on the piezoresistive effect experienced by certain materials upon elastic deformation (discovered by Lord Kelvin, 1856). The word "piezoresistive" derives from the Greek "piezein," which means "to press." The piezoresistive effect involves a change in the resistance R of an electrical conductor [$R = \rho l/A$, where ρ is the material (Ω/cm), resistivity, l the conductor length, and A the transverse section area] as a consequence of a change in their geometrical parameters (at the macroscopic level) originated by an external stimulus. In certain materials, however, an equally important part of the piezoresistive effect is due to the change in resistivity ρ.

Piezoresistive materials are not themselves able to generate an electrical signal when strained; they need to be supplied with an external voltage source. If a voltage is applied between the extremities of a piezoresistive bar whose geometry is changing, the current also changes according to the change in resistance, in accordance with Ohm's law. In this very elementary example, the current that flows through the piezoresistive bar is the output electrical signal directly related (by means of resistance variation) to the change of an external stimulus. Since piezoresistive materials upon deformation transform mechanical energy into electrical energy, they can be employed in the fabrication of transducers to make physical sensors. Piezoresistive sensors are called *active* sensors, in contrast with *passive* sensors, which themselves generate an electrical signal when stimulated and therefore do not need to be supplied with an external voltage source (1). Active sensors need specific supply circuits depending on the transducer technology.

Piezoresistive sensors are used to perform direct measurements of dynamic and geometric parameters (2) such as acceleration, cracks, creep, deformation, displacement, fatigue, flow, force, height, level, mass, pressure, and torque.

The fabrication of piezoresistive sensors involves the use of very different materials, such as conductive elastomers, carbon fiber, pure metals, or alloys (commonly with nickel and copper). More sophisticated processes are based on thin-film, thick-film, and solid-state technology (2).

BASIC THEORY

Let R be the resistance of an electrically conducting bar in the quiescent state at room temperature. By differentiating the expression

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

we have

$$\begin{aligned} dR &= \frac{\partial R}{\partial \rho} d\rho + \frac{\partial R}{\partial l} dl + \frac{\partial R}{\partial A} dA \\ &= \frac{l}{A} d\rho + \frac{\rho}{A} dl - \frac{\rho l}{A^2} dA \end{aligned}$$

and dividing by R we finally obtain

$$\frac{dR}{R} = \frac{l}{A} \cdot \frac{d\rho}{R} + \frac{\rho}{A} \cdot \frac{dl}{R} - \frac{\rho l}{A^2} \cdot \frac{dA}{R}$$

which reduces to

$$= \frac{d\rho}{\rho} + \frac{dl}{l} - \frac{dA}{A} \tag{1}$$

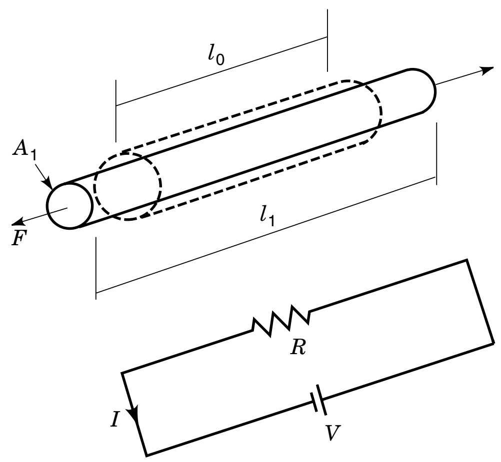

Figure 1. Piezoresistive bar to which traction is applied.

Consider now a piezoresistive bar with cylindrical geometry (see Fig. 1), to which an electric field E_l is applied along the longitudinal direction, and suppose that, upon elongation, the initial value of the piezoresistor changes to the final value (the initial values of the length, the diameter, and the resistivity change too). As a consequence of the length increase a reduction in the cross sectional area occurs too, according to Poisson's ratio $\nu = \epsilon_d/\epsilon_l$ (diametral strain per unit longitudinal strain).

It can be easily shown that the longitudinal gauge factor is given by

$$F_l = 1 + 2\nu + \frac{1}{\epsilon_l} \cdot \frac{d\rho}{\rho} \tag{2}$$

In the same manner also a transverse gauge factor can be defined.

Values of the longitudinal gauge factor for some commonly used materials are given in Table 1.

CONDUCTIVE RUBBERS

Conductive rubbers are commonly made by loading silicone-based polymers with conducting powder (preferably graphite) or grains of small dimensions, depending on the applications. Polymer strain gauges are largely used in robotic applications for making highly robust and compliant prototype tactile sensors that resist damage and accommodate inaccuracy during the end-effector positioning and the grasp. Different arrangements have been proposed, including row-by-column matrices protected by Mylar films (Fig. 2) or silicone rubber skin. They use polyurethane foam to increase compliance, as well as conductive rubber wires for electrical connection with the acquisition electronic unit, preferably realized in hybrid technology (5).

Table 1. Resistivity and Longitudinal Gauge Factor of the Most Common Materials for Piezoresistive Sensors

Material	Resistivity ρ ($\times 10^{-6}\ \Omega \cdot$ cm)	F_l
Silver (Ag)	1.628	3.5
Aluminum (Al)	2.828	3.3
Gold (Au)	2.4	3.7
Copper (Cu)	1.724	2.9
Iron (Fe)	10	3.2
Nichrome V ($Ni_{80}Cr_{20}$)	7.1	101
Nickel (Ni)	6.84	−11
Platinum (Pt)	10	4.4

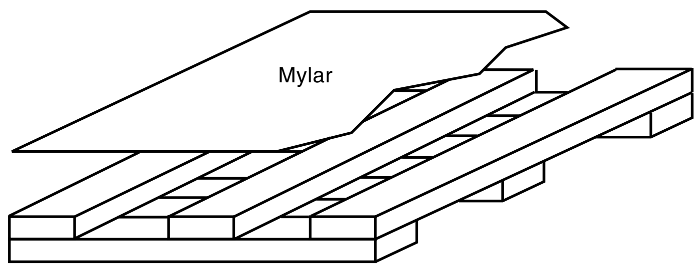

Figure 2. Conductive rubber tactile sensor.

On applying a force to the rubber matrix (5), the contact area between the rubber increases and the resistance R decreases. The maximum useful load reaches about 454 kg. At low loads, the sensor response follows the law $R = k/F$, where $k = 4$ MΩkg and F is the applied force.

METAL STRAIN GAUGES

The most popular and reliable technology, at very low cost compared with other technologies available today, is that of metal strain gauges. The transducers are usually made with a metal stripe a few micrometers thick (6). The length l can be much larger than the width (see Fig. 3); a typical thickness is about 5 μm, and typical values of the resistance range from 120 Ω to 750 Ω. The metal foil grid is backed by a plastic carrier with a thickness of about 25 μm. The longitudinal and transverse gauge factors are about 2 and 0 respectively. Conventional metal foils of piezoresistive strain gauges are particularly suitable for mounting on bodies on which the strain must be measured. They are also called *bonded* strain gauges (3). (*Unbonded* strain gauges are made of several conducting wires suspended between two insulating pins; they are excellent force transducers, but they are cumbersome and also difficult to fabricate.)

Bonded gauges are placed directly on the surface of the body of which the strain is to be measured. The initial dimen-

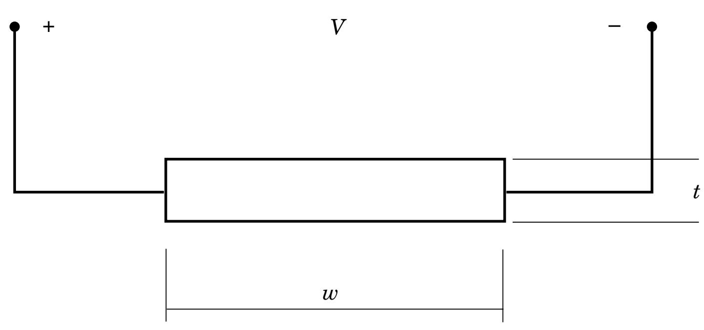

Figure 3. Cross section of a planar strain gauge to which an electrical potential V is applied along the width w, while a traction is applied along the length l (orthogonal to the page).

sion can be carefully reduced by etching away very small parts of the backing polymer carrier. The surface must be clean and dry to ensure good adhesion of the special glues and catalysts used (3,7). Because of its geometry, the piezoresistor is mounted with the grid parallel to the direction of the dominant strain (*longitudinal strain*), although the body can also experience a secondary strain (*transverse strain*) in the orthogonal direction.

A particular geometric disposition of more than one strain gauge, a *rosette* [see Fig. 1(c)] is used to sense nonuniform force fields involving multicomponent strains.

Metal strain gauges are not suitable for miniaturization.

THICK-FILM STRAIN GAUGES

Thick-film strain gauges consist of special resistive inks, loaded with submicrometer conducting particles and insulating glass parts suspended in viscous organic fluids (8). They are screened and fired on ceramic substrates. The strain sensitivity is strongly influenced by the resistivity, composition, structure, and nature of the conductive grains, and by the direction of the strain with respect to the electric field. The conduction mechanism and the strain sensitivity are dominated by the tunneling effect. A longitudinal gauge factor $GF_L = 13.8$ and a transverse gauge factor $GF_T = 11.6$ have been measured. Thick-film strain gauges are preferred for high-temperature operation (350°C) and in hostile environments (2). They are not satisfactory for miniaturization.

THIN-FILM STRAIN GAUGES

Thin-film strain gauges, usually made of SnO or SiO–Cr, are deposited on ceramic substrates by vacuum processes such as evaporation and sputtering. Device miniaturization is possible, and the maximum temperature of operation reaches about +150°C.

SEMICONDUCTOR STRAIN GAUGES

In contrast with the previous technologies, which are largely employed for the fabrication of universal strain gauges in force field measurement, semiconductor monolithic sensors are limited to pressure and acceleration measurement. Micromachining and integrated circuit (IC) technologies allow the fabrication of microsensors and microactuators for a temperature of operation not more than +120°C. Semiconductors experience an additional piezoelectric effect, which leads to small differences in the gauge factor $GF = 2 - K$, where 2 is a pure geometrical factor and

$$K = -\frac{1}{\epsilon} \cdot \frac{d(n\mu)}{n\mu}\bigg|_{\epsilon}$$

takes account of the semiconductor nature of the material. In this expression ϵ can be the longitudinal or transverse strain, n is the number of the charge carriers, and μ is the mobility (2).

TYPES OF PIEZORESISTIVE DEVICES

Pressure Transducers

Pressure transducers convert pressure variations into resistance variations. Both unbonded and bonded metal strain gauges, and also sputtered thin-film gauges are used for this purpose. The transducers are usually located on the back side of a membrane, and the pressure is applied to the opposite side (9).

Force Transducers

Force transducers are realized by using metal, both unbonded and bonded, and semiconductor strain gauges. Force measurements are usually performed by combining shear stresses with cantilever beams of different configurations (9).

Accelerometers

Accelerometers, based on metal bonded strain gauges and semiconductor strain gauges, convert the displacement of a mass–spring system into a variation of resistance. In the most common devices, the gauges are bonded to a cantilever beam terminated with a seismic mass (9).

Torque Transducers

Torque transducers sense the shear stresses in a torsion bar as a consequence of the applied torque. Usually semiconductor and bonded metal foil strain gauges, in a cruciform arrangement, are used for this application (9).

Displacement Transducers

Displacements are measured through the deflection of a bending beam. The strain gauges are mounted to sense both the tension and the compression of the beam. The beam is deflected by a sensing shaft (9).

BIBLIOGRAPHY

1. J. J. Carr, *Sensors and Circuits,* Englewood Cliffs, NJ: Prentice-Hall, 1993.
2. K. Bethe, The scope of the strain gage principle, *Proc. Int. Conf. VLSI Comput. Peripherals. VLSI and Microelectron. Applications Intell. Peripherals Interconnection Networks,* Washington, DC, May 1989, Vol. 3, pp. 31–38.
3. P. Dario, M. Bergamasco, and A. Fiorillo, Force and tactile sensing for robots, in P. Dario (ed.), *Sensors and Sensory Systems for Advanced Robots,* Berlin: Springer-Verlag, 1988.
4. R. A. Russel, An imaging force sensor for robotics applications, *National Conference on Robotics,* Melbourne, 1984, pp. 123–127.
5. Interlink Electronics, The force sensing resistor, a new tool in sensor technology, Technical Paper, Santa Barbara, CA, June 1986.
6. HBM, Darmstadt, Germany.
7. D. Hagner, Metal strain gages, in J. Webster (ed.), *Tactile Sensors for Robotics and Medicine,* New York: Wiley, 1988.
8. C. Canali et al., Piezoresistive effects in thick-film resistors, *J. Appl. Phys.,* **51** (6): 3282–3287, 1980.
9. H. N. Norton, *Handbook of Transducers,* Englewood Cliffs, NJ: Prentice-Hall, 1989.

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PILOTAGE, HELICOPTER. See HELICOPTER NIGHT PILOTAGE.

PIPELINED PROCESSORS. See ARRAY AND PIPELINED PROCESSORS.

PLANAR LINES. See STRIPLINES.

PLANAR TRANSMISSION LINES. See MICROSTRIP LINES.

PLAN, DO, CHECK, AND ACT (PDCA). See SOFTWARE PROJECT MANAGEMENT.