Technology Brief 4
Resistive Sensors

Resistive sensors can convert many physical parameters in our environment into a resistance that varies with temperature, light, pressure, moisture, chemical composition, sound, or other inputs. This variable resistance will then change the voltage or current in a circuit, which can be further manipulated in an electrical system to produce a desired output (turning on a warning light or buzzer, adjusting a valve, or otherwise control the pressure/light/heat/sound automatically). When a system measures a parameter (e.g., temperature) in order to control that parameter, the process is called a ***feedback loop***. Sensors are a very important part of a feedback system.

So how do resistive sensors work? The resistance R of a semiconductor accounts for the reduction in the electrons' velocities due to collisions with the much larger atoms of the conducting material (see Technology Brief 3). The question is: What happens to R if we disturb the atoms of the conductor by applying an external, nonelectrical ***stimulus***, such as heating or cooling it, stretching or compressing it, or shining light on it? Through proper choice of materials, we can *modulate* (change) the magnitude of R in response to such external stimuli.

Piezoresistive Sensors (Pressure, Bending, Force, etc.)

In 1856, Lord Kelvin discovered that applying a mechanical load on a bar of metal changed its resistance. Over the next 150 years, both theoretical and practical advances made it possible to describe the physics behind this effect in both conductors and semiconductors. The phenomenon is referred to as the ***piezoresistive effect*** (**Fig. TF4-1**) and is used in many practical devices to convert a mechanical signal into an electrical one. Such sensors (**Fig. TF4-2**) are called ***strain gauges***. Piezoresistive sensors are used in a wide variety of consumer applications, including writing styluses for tablets (some high-precision styluses are resistive and others are capacitive—which we will learn about in Chapter 5), robot toy "skins" that sense force, microscale gas-pressure sensors, and micromachined accelerometers that sense acceleration. They all use piezoresistors in electrical circuits to generate a signal from a mechanical stimulus.

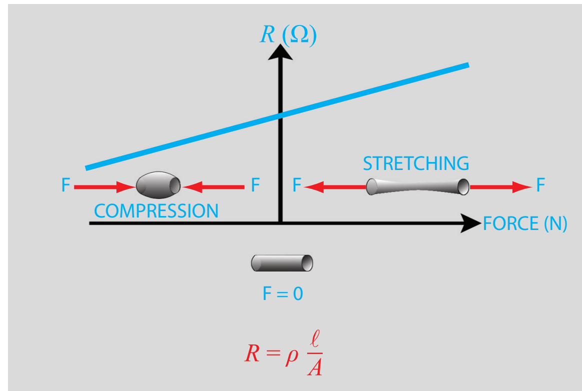

Figure TF4-1: Piezoresistance varies with applied force. The word "piezein" means "to press" in Greek.

In its simplest form, a resistance change ΔR occurs when a mechanical pressure P (N/m^2) is applied along the axis of the resistor (**Fig. TF4-1**)

$$\Delta R = R_0 \alpha P,$$

where R_0 is the unstressed resistance and α is known as the ***piezoresistive coefficient*** (m^2/N). The piezoresistive coefficient is a material property, and for crystalline materials (such as silicon), the piezoresistive coefficient also varies depending on the direction of the applied pressure (relative to the crystal planes of the material). When the horizontal and vertical components are different the material is called ***anisotropic***. The total resistance of a piezoresistor under stress is therefore given by

$$R = R_0 + \Delta R = R_0(1 + \alpha P).$$

The pressure P, which usually is called the ***mechanical stress*** or ***mechanical load***, is equal to F/A, where F is the force acting on the piezoresistor and A is the cross-sectional area it is acting on. The sign of P is defined as positive for a compressive force and negative for a stretching force. The piezoresistive coefficient α usually has a negative value, so the product αP leads to a decrease in R for compression and an increase for stretching.

Thermistor Sensors

Changes in temperature also can lead to changes in the resistance of a piece of conductor or semiconductor;

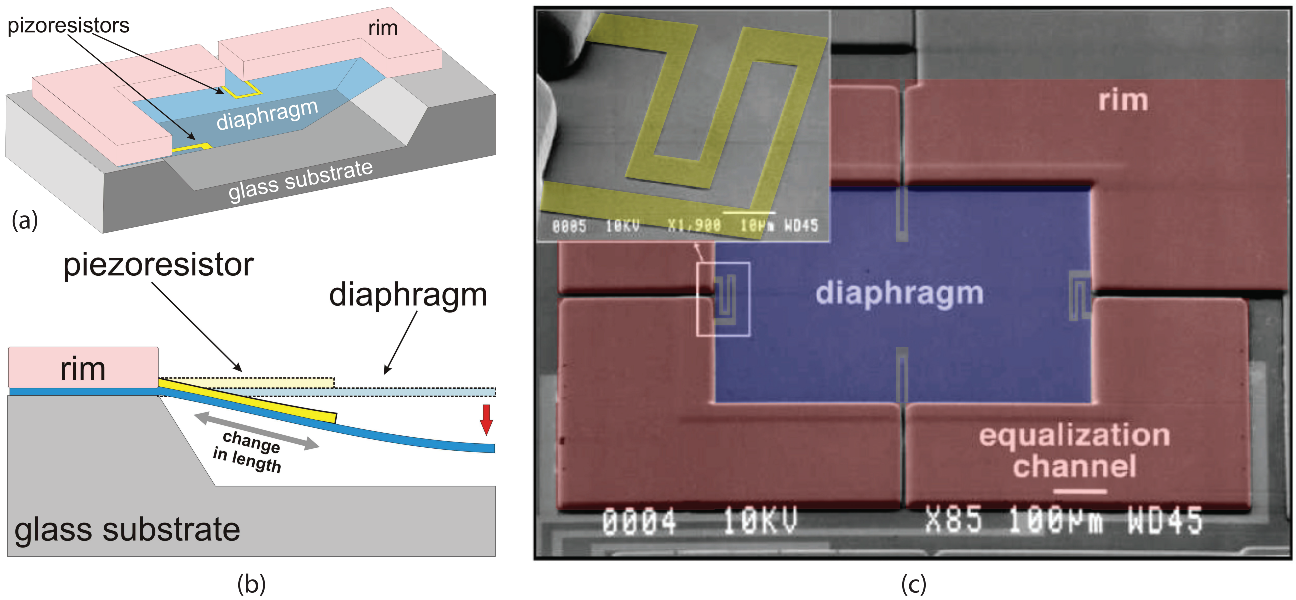

Figure TF4-2: A microfabricated pressure sensor utilizing piezoresistors as sensors. (a) A thin diaphragm (blue) is suspended over a depression etched into a glass substrate (grey). Serpentine piezoresistors (yellow) are patterned onto the membrane. (b) Differences in pressure between between the ambient and the gas in the depression will move the membrane. When this happens, the resistors stretch (or compress), changing their resistance as explained in the text. (c) A false color scanning electron micrograph of an actual microfabricated pressure sensor. Note the piezoresistors (yellow) patterned along the four sides of the diaphragm and the white, 100 μm scale bar. (Courtesy of Khalil Najafi, University of Michigan.)

when used as a sensor, such an element is called a ***thermistor***. As a simple approximation, the change in resistance can be modeled as

$$\Delta R = k\,\Delta T,$$

where ΔT is the temperature change (in degrees C) and k is the first-order temperature coefficient of resistance ($\Omega/^\circ$C). Thermistors are classified according to whether k is negative or positive (i.e., if an increase in temperature decreases or increases the resistance). This approximation works only for small temperature changes; for larger swings, higher-order terms must be included in the equation. Resistors used in electrical circuits that are not intended to be used as sensors are manufactured from materials with the lowest k possible, since circuit designers do not want their resistors changing during operation. In contrast, materials with high values of k are desirable for sensing temperature variations. Care must be taken, however, to incorporate into the sensor response the self-heating effect that occurs due to having a current passing through the resistor itself (as in the flow sensor shown in **Fig. TF4-3**).

Thermistors are used routinely in modern thermostats, cell phones, automotive and industrial applications, weather monitoring, and battery-pack chargers (to prevent batteries from overheating). Thermistors also have found niche applications (**Fig. TF4-3**) in low-temperature sensing and as fuse replacements (for thermistors with large, positive k values). In the case of current-limiting fuse replacements, a large enough current self-heats the thermistor, and the resistance increases. There is a threshold current above which the thermistor cannot be cooled off by its environment; as it continues to get hotter, the resistance continues to increase, which in turn, causes even more self-heating. This "runaway" effect rapidly shuts current off almost entirely. Thermistors are specified based on their linear range where resistance varies linearly with the temperature, and a wide variety of options are available.

Moisture and Chemical Sensors

Resistive sensors can also be built with two electrodes measuring the material between them. A simple moisture

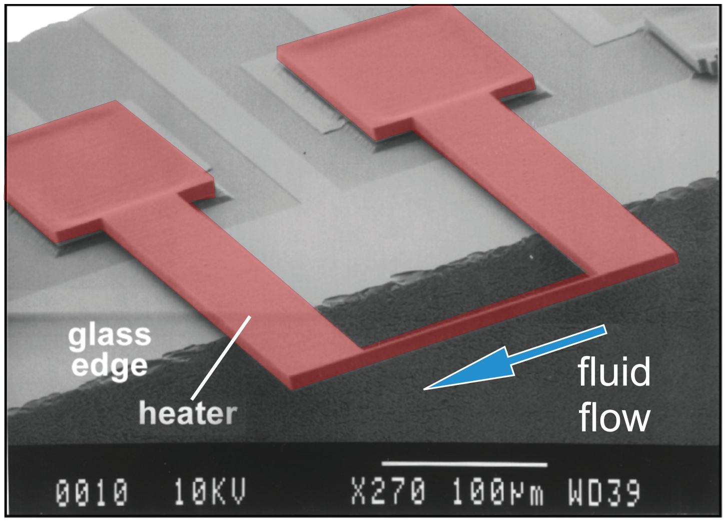

Figure TF4-3: This micromachined anemometer (flow meter) is a thermistor that measures fluid velocity. The resistor (red) serves as both a heater and a thermistor. During operation, a voltage across the resistor produces a current ($I = V/R$) which heats the resistor (recall the heat power, $P = V * I$). As fluid flows by the resistor (blue), the flow draws away heat. Since increasing the flow increases the cooling of the resistor and temperature changes the resistance, the flow can be inferred from the thermistor. (Courtesy of Khalil Najafi, University of Michigan.)

sensor you can build yourself consists of two electrodes with an absorbing material between them (Fig. TF4-4). Just draw two thick pencil (graphite) lines on paper, clip to them with alligator clips, and measure the resistance with your myDAQ. Then drip water between the two lines, so that it makes contact between them. The resistance will immediately drop in magnitude.

In a similar approach, resistive sensors can sometimes be used to determine chemical composition of a liquid material. The resistivity of the material depends strongly on the number of dissolved or loose ions in the material (see Table 2-1). Deionized water has high resistivity, drinking water has moderate resistivity, and sea water has low resistivity. Placing two electrodes into a container of fluid, or running fluid over two electrodes in a microfluidic system can be used to measure the resistivity of the material and hence its chemical composition. This is often used as a simple way to monitor the purity of drinking water.

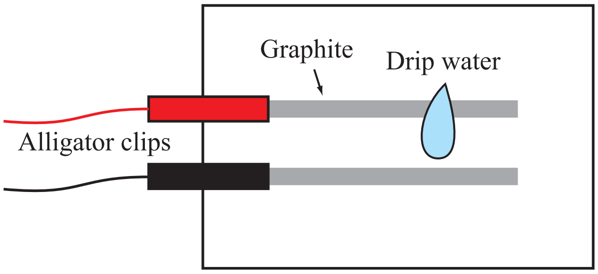

Figure TF4-4: Increased ions (from dissolved solids, for example) increase the conductivity (reduce resistivity), which can be measured by an ohmmeter.