Technology Brief 4: Resistors as Sensors

The relationship between the voltage across a conductor and the current through it is given by Ohm's law, \( V = IR \). The resistance \( R \) of the conductor accounts for the reduction in the electrons' velocities due to collisions with the much larger atoms of the conducting material (see Technology Brief 3 on page 38). The question is: What happens to \( R \) if we disturb the atoms of the conductor by applying an external, non-electrical stimulus, such as heating or cooling it, stretching or compressing it, or shining light on it? Through proper choice of materials, we actually can modulate (change) the magnitude of \( R \) by applying such external stimuli, and this forms the basis of many common sensors.

Piezoresistive Sensors

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 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.

In its simplest form, a resistance change \( \Delta R \) 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 \( \alpha \) 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). 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 compressional force and negative for a stretching force. The piezoresistive coefficient \( \alpha \) usually has a negative value, so the product \( \alpha P \) leads to a decrease in \( R \) for compression and an increase for stretching.

![Figure TF4-1: Piezoresistance varies with applied force. The word “piezein” means “to press” in Greek.](image-url)
Thermistor Sensors

Changes in temperature also can lead to changes in the resistance of a piece of conductor or semiconductor; 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 $\Delta T$ is the temperature change (in degrees C) and $k$ is the first-order temperature coefficient of resistance ($\Omega/°C$). 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.

Thermistors are used routinely in modern thermostats and in 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.

Figure TF4-2: A microfabricated pressure sensor developed at the University of Michigan. It uses piezoresistors to detect deformation of a membrane; when the membrane (white) deflects, it stretches the piezoresistor and the resistance changes. (Courtesy of Khalil Najafi, University of Michigan.)

Figure TF4-3: This micromachined anemometer is a thermistor that measures fluid velocity; as fluid flows by, it cools the thermistor at different rates, depending on the fluid velocity. (Courtesy of Khalil Najafi, University of Michigan.)
Technology Brief 5: Light-Emitting Diodes (LEDs)

Light-emitting diodes (LEDs) are a mainstay of lighting in many manufactured products, from consumer electronics to home appliances to high-efficiency tail-lights for cars. These solid-state semiconductor devices can be fabricated to emit light (Fig. TF5-1) in very narrow bands, centered around any desired wavelength in the spectral range encompassing the infrared, visible, and ultraviolet segments of the electromagnetic spectrum. Modern LEDs are manufactured in a staggering variety of shapes, sizes, and colors. Compared with conventional phosphorescent light bulbs, LEDs have many advantages. Light-emitting diodes respond much faster (microseconds or less), can be made to emit light in a very narrow wavelength band (appear to be a single color), emit more light per watt of electrical energy input, have very long lifetimes (>100,000 hours), and can be integrated directly into semiconductor circuits, printed circuit boards, and in light-focusing packages. LEDs are now inexpensive enough that they are being integrated routinely into street lights, automobile lights, high-efficiency flashlights, and even woven into clothes (e.g., Philips Research Lumalive textiles).

LEDs are a specific type of the much-larger diode family, whose basic behavior we discussed earlier in Section 2-7. When a voltage is applied in the forward-biased direction across an LED, current flows and photons are emitted (Fig. TF5-2). This occurs because as electrons surge through the diode material they recombine with charge carriers in the material and release energy. The energy is released in the form of photons (quanta of light). The energy of the emitted photon (and hence, its wavelength) depends on the type of material used to make the diode. For example, a diode made of aluminum gallium arsenide (AlGaAs) emits red light, while a diode made from indium gallium nitride (InGaN) emits bluish light. Extensive research over many decades has yielded materials that can emit photons at practically any wavelength across a broad spectrum, extending from the infrared to the ultraviolet. Various “tricks” also have been employed to modify the emitted light after emission. To make white light diodes, for example, certain blue light diodes can be coated with crystal powders which convert the blue light to broad-spectrum “white” light. Other coatings that modify the emitted light (such as quantum dots) are still the subject of research.

In addition to semiconductor LEDs, a newer class of devices called Organic Light Emitting Diodes (OLEDs) are the subject of intense research efforts. OLEDs operate in a manner analogous to conventional LEDs, but the material used is composed of organic molecules (often polymers). OLEDs are lighter, often flexible, and have the potential to revolutionize handheld and lightweight displays, such as those used in phones, PDAs and flexible screens (see Technology Brief 6 on page 106).
Technology Brief 6: Display Technologies

From cuneiform-marked clay balls to the abacus to today's digital projection technology, advances in visual displays have accompanied almost every major leap in information technology. While the earliest "modern" computers relied on cathode ray tubes (CRT) to project interactive images, today's computers can access a wide variety of displays ranging from plasma screens and LED arrays to digital micromirror projectors, electronic ink, and virtual reality interfaces. In this Technology Brief, we will review the major technologies currently available for two-dimensional visual displays.

Cathode Ray Tube (CRT)

The earliest computers relied on the same technology that made the television possible. In a CRT television or monitor (Fig. TF6-1), an electron gun is placed behind a positively charged glass screen, and a negatively charged electrode (the cathode) is mounted at the input of the electron gun. During operation, the cathode emits streams of electrons into the electron gun. The emitted electron stream is steered onto different parts of the positively charged screen by the electron gun; the direction of the electron stream is controlled by the electric field of the deflecting coils through which the beam passes. The screen is composed of thousands of tiny dots of phosphorescent material arranged in a two-dimensional array. Every time an electron hits a phosphor dot, it glows a specific color (red, blue, or green). A pixel on the screen is composed of phosphors of these three colors. In order to make an image appear to move on the screen, the electron gun constantly steers the electron stream onto different phosphors, lighting them up faster than the eye can detect the changes, and thus, the images appear to move. In modern color CRT displays, three electron guns shoot different electron streams for the three colors.

Interestingly, the basic concept behind the CRT is still very relevant. A new technology called Field Emission Display (FED) has emerged, which uses a thin film of atomically sharp electron emitter tips (carbon nanotubes can be used for this purpose) to generate the electrons. The electrons emitted by the film collide with phosphor elements just as in the traditional CRT. The primary advantage of this type of "flat-panel" display is that it can provide a wider viewing angle (i.e., one can look at an FED screen at a sharp angle and still see a good image) than possible with conventional LCD or LED technology (discussed next).

![Figure TF6-1: Schematic of CRT operation.](image-url)
Liquid Crystal Displays (LCD)

LCDs are used in digital clocks, cellular phones, desktop and laptop computers, and some televisions and other electronic systems. They offer a decided advantage over other display technologies (such as cathode ray tubes) in that they are lighter and thinner and consume a lot less power to operate. LCD technology relies on special electrical and optical properties of a class of materials known as liquid crystals, first discovered in the 1880s by botanist Friedrich Reinitzer. In the basic LCD display, light shines through a thin stack of layers as shown in Fig. TF6-2. Each stack consists of layers in the following order (starting from the viewer's eye): color filter, vertical (or horizontal) polarizer filter, glass plate with transparent electrodes, liquid crystal layer, second glass plate with transparent electrodes, horizontal (or vertical) polarizer filter. Light is shone from behind the stack (called the backlight). As light crosses through the layer stack, it is polarized along one direction by the first filter. If no voltage is applied on any of the electrodes, the liquid crystal molecules align the filtered light so that it can pass through the second filter. Once through the second filter, it crosses the color filter (which allows only one color of light through) and the viewer sees light of that color. If a voltage is applied between the electrodes on the glass plates (which are on either side of the liquid crystal), the induced electric field causes the liquid crystal molecules to rotate. Once rotated, the crystals no longer align the light coming through the first filter so that it can pass through the second filter plate. If light cannot cross, the area with the applied voltage looks dark. This is precisely how simple hand-held calculator displays work; usually the bright background is made dark every time a character is displayed.

Figure TF6-2: Schematic of LCD operation.

Modern flat-profile computer screens and laptops use a version of the LCD called thin-film transistor (TFT) LCD; these also are known as active matrix displays. In TFT LCDs, several thin films are deposited on one of the glass substrates and patterned into transistors. Each color component of a pixel has its own microscale transistor that controls the voltage across the liquid crystal; since the transistors only take up a tiny portion of the pixel area, they effectively are invisible. Thus, each pixel has its own electrode driver built directly into it. This specific feature enabled the construction of the flat high-resolution screens now in common use with desktops (and made the CRT display increasingly obsolete). Since LCD displays also weigh considerably less than a CRT tube, they enabled the emergence of laptop computers in the 1980s. Early laptops used large, heavy monochrome LCDs; most of today's palmtop and laptop systems use active-matrix displays.

Light-Emitting Diode (LED) Displays

A fundamental advance over LCDs is the use of tiny light-emitting diodes (LED) in large pixel arrays on flat screens (see Technology Brief 5: LEDs on page 96). Each pixel in an LED display is composed of three LEDs (one each of red, green, and blue). Whenever a current is made to pass through a particular LED, it emits light at its particular color. In this way, displays can be made flatter (i.e., the LED circuitry takes up less room than an electron gun or LCD) and
larger (since making large, flat LED arrays technically is less challenging than giant CRT tubes or LCD displays). Unlike LCDs, LED displays do not need a backlight to function and easily can be made multi-color. Modern LED research is focused mostly on flexible and organic LEDs (OLEDs), which are made from polymer light-emitting materials and can be fabricated on flexible substrates (such as an overhead transparency). Flexible displays of this type have been demonstrated by several groups around the world. Organic LEDs emit less light than traditional solid-state LEDs, however, and based on current technology, the lifetime of an OLED usually is shorter than desired for commercial applications.

Plasma Displays
Plasma displays have been around since 1964 when invented at the University of Illinois. While attractive due to their low profile, large viewing angle, brightness, and large screen size, they largely were displaced in the 1980s in the consumer market by LCD displays for manufacturing-cost reasons. In the late 1990s, plasma displays became popular for high-definition television (HDTV) systems. Each pixel in a plasma display contains one or more microscale pocket(s) of trapped noble gas (usually neon or xenon); electrodes patterned on a glass substrate are placed in front and behind each pocket of gas (Fig. TF6-3). The back of one of the glass plates is coated with light-emitting phosphors. When a sufficient voltage is applied across the electrodes, a large electric field is generated across the noble gas, and a plasma (ionized gas) is ignited. The plasma emits ultraviolet light which impacts the phosphors; when impacted with UV light, the phosphors emit light of a certain color (blue, green, or red). In this way, each pocket can generate one color.

Electronic Ink
Electronic ink, e-paper, or e-ink are all names for a set of display technologies made to look like paper with ink on it. In all cases, the display is very thin (almost as thin as real paper), does not use a backlight (ambient light is reflected off the display, just like real paper), and little to no power is consumed when the image is kept constant. The first version of e-paper was invented in the 1970s at Xerox, but it was not until the 1990s that a commercially viable version was developed at MIT. Many companies are now in the process of developing displays for laptops, "e-newspapers," e-books, cell phones, and the like. As of 2006, the largest mass-market display is an 8-inch XGA display from E-Ink, but many newer versions (including color displays) are in the pipeline.
Digital Light Processing (DLP)

Digital light processing (DLP) is the name given to a technology that uses arrays of individual, micro-mechanical mirrors to manipulate light at each pixel position. Invented in 1987 by Dr. Hornbeck at Texas Instruments, this technology has revolutionized projection technology; most of today’s small, inexpensive digital projectors are made possible by DLP chips. DLP also is used heavily in large, rear-projection televisions (where it competes with LCD and a variant of LCD). A basic DLP consists of an array of metal micromirrors, each about 100 micrometers on a side (Fig. TF6-4 (inset)). One micromirror corresponds to one pixel on a digital image. Each micromirror is mounted on micromechanical hinges and can be tilted towards or away from a light source several thousand times per second! The mirrors are used to reflect light from a light source (housed within the television or projector case) and through a lens to project it either from behind a screen (as is the case in rear-projection televisions) or onto a flat surface (in the case of projectors), as in (Fig. TF6-4). If a micromirror is tilted away from the light source, that pixel on the projected image becomes dark (since the mirror is not passing the light onto the lens). If it is tilted towards the light source, the pixel lights up. By varying the relative time a given mirror is in each position, grey values can be generated as well. Color can be added by using multiple light sources and either one chip (with a filter wheel) or three chips. The three-chip color DLP used in high-resolution cinema systems can purportedly generate 35 trillion different colors!

![Figure TF6-4: DLP](image-url)