Electrical resistance and conductance

The electrical resistance of an electrical conductor is the opposition to the passage of an electric current through that conductor; the inverse quantity is electrical conductance, the ease at which an electric current passes. Electrical resistance shares some conceptual parallels with the mechanical notion of friction. The SI unit of electrical resistance is the ohm (Ω), while electrical conductance is measured in siemens (S).

An object of uniform cross section has a resistance proportional to its resistivity and length and inversely proportional to its cross-sectional area. All materials show some resistance, except for superconductors, which have a resistance of zero.

The resistance (R) of an object is defined as the ratio of voltage across it (V) to current through it (I), while the conductance (G) is the inverse:

\[ R = \frac{V}{I}, \quad G = \frac{I}{V} \]

For a wide variety of materials and conditions, V and I are directly proportional to each other, and therefore R and G are constant (although they can depend on other factors like temperature or strain). This proportionality is called Ohm's law, and materials that satisfy it are called "Ohmic" materials.

In other cases, such as a diode or battery, V and I are not directly proportional, or in other words the I–V curve is not a straight line through the origin, and Ohm's law does not hold. In this case, resistance and conductance are less useful concepts, and more difficult to define. The ratio V/I is sometimes still useful, and is referred to as a "chordal resistance" or "static resistance", as it corresponds to the inverse slope of a chord between the origin and an I–V curve. In other situations, the derivative \( \frac{dV}{dT} \) may be most useful; this is called the "differential resistance".

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### [edit] Introduction

The hydraulic analogy compares electric current flowing through circuits to water flowing through pipes. When a pipe (left) is filled with hair (right), it takes a larger pressure to achieve the same flow of water. Pushing electric current through a large resistance is like pushing water through a pipe clogged with hair: It requires a larger push (electromotive force) to drive the same flow (electric current).

In the hydraulic analogy, current flowing through a wire (or resistor) is like water flowing through a pipe, and the voltage drop across the wire is like the pressure drop which pushes water through the pipe. Conductance is proportional to how much flow occurs for a given pressure, and resistance is proportional to how much pressure is required to achieve a given flow. (Conductance and resistance are reciprocals.)

The voltage drop (i.e., difference in voltage between one side of the resistor and the other), not the voltage itself, provides the driving force pushing current through a resistor. In hydraulics, it is similar: The pressure difference between two sides of a pipe, not the pressure itself, determines the flow through it. For example, there may be a large water pressure above the pipe, which tries to push water down through the pipe. But there may be an equally large water pressure below the pipe, which tries to push water back up through the pipe. If these pressures are equal, no water will flow. (In the image at right, the water pressure below the pipe is zero.)
The resistance and conductance of a wire, resistor, or other element is generally determined by two factors: geometry (shape) and materials.

Geometry is important because it is more difficult to push water through a long, narrow pipe than a wide, short pipe. In the same way, a long, thin copper wire has higher resistance (lower conductance) than a short, thick copper wire.

Materials are important as well. A pipe filled with hair restricts the flow of water more than a clean pipe of the same shape and size. In a similar way, electrons can flow freely and easily through a copper wire, but cannot as easily flow through a steel wire of the same shape and size, and they essentially cannot flow at all through an insulator like rubber, regardless of its shape. The difference between, copper, steel, and rubber is related to their microscopic structure and electron configuration, and is quantified by a property called resistivity.

[edit] Conductors and resistors

A 65 Ω resistor, as identified by its electronic color code (blue–green–black–gold). An ohmmeter could be used to verify this value.

Objects such as wires that are designed to have low resistance so that they transfer current with the least loss of electrical energy are called conductors. Objects that are designed to have a specific resistance so that they can dissipate electrical energy or otherwise modify how a circuit behaves are called resistors. Conductors are made of high-conductivity materials such as metals, in particular copper and aluminium. Resistors, on the other hand, are made of a wide variety of materials depending on factors such as the desired resistance, amount of energy that it needs to dissipate, precision, and costs.

[edit] Ohm's law

The current-voltage characteristics of four devices: Two resistors, a diode, and a battery. The horizontal axis is voltage drop, the vertical axis is current. Ohm's law is satisfied when the graph is a straight line through the origin. Therefore, the two resistors are "ohmic", but the diode and battery are not.

Main article: Ohm's law

Ohm's law is an empirical law relating the voltage $V$ across an element to the current $I$ through it:

$$V \propto I$$
(V is directly proportional to I). This law is not always true: For example, it is false for diodes, batteries, etc. However, it is true to a very good approximation for wires and resistors (assuming that other conditions, including temperature, are held fixed). Materials or objects where Ohm's law is true are called "ohmic".

For ohmic materials, the resistance $R$ and conductance $G$ are defined by:

$$R = \frac{V}{I}, \quad G = \frac{I}{V}$$

Therefore, resistance and conductance are inverses:

$$G = \frac{1}{R}$$

[edit] Relation to resistivity and conductivity

![A piece of resistive material with electrical contacts on both ends.](image)

*Main article: Electrical resistivity and conductivity*

The resistance of a given object depends primarily on two factors: What material it is made of, and its shape. For a given material, the resistance is inversely proportional to the cross-sectional area; for example, a thick copper wire has lower resistance than an otherwise-identical thin copper wire. Also, for a given material, the resistance is proportional to the length; for example, a long copper wire has higher resistance than an otherwise-identical short copper wire. The resistance $R$ and conductance $G$ of a conductor of uniform cross section, therefore, can be computed as

$$R = \rho \frac{\ell}{A},$$

$$G = \sigma \frac{A}{\ell}.$$
where $l$ is the length of the conductor, measured in metres $[m]$, $A$ is the cross-section area of the conductor measured in square metres $[m^2]$, $\sigma$ ($\text{sigma}$) is the electrical conductivity measured in siemens per meter ($S\cdot m^{-1}$), and $\rho$ ($\text{rho}$) is the electrical resistivity (also called specific electrical resistance) of the material, measured in ohm-metres ($\Omega\cdot m$). The resistivity and conductivity are proportionality constants, and therefore depend only on the material the wire is made of, not the geometry of the wire. Resistivity and conductivity are reciprocals: $\sigma = \frac{1}{\rho}$. Resistivity is a measure of the material's ability to oppose electric current.

This formula is not exact: It assumes the current density is totally uniform in the conductor, which is not always true in practical situations. However, this formula still provides a good approximation for long thin conductors such as wires.

Another situation for which this formula is not exact is with alternating current (AC), because the skin effect inhibits current flow near the center of the conductor. Then, the geometrical cross-section is different from the effective cross-section in which current is actually flowing, so the resistance is higher than expected. Similarly, if two conductors are near each other carrying AC current, their resistances will increase due to the proximity effect. At commercial power frequency, these effects are significant for large conductors carrying large currents, such as busbars in an electrical substation, or large power cables carrying more than a few hundred amperes.

[edit] What determines resistivity?

Main article: Electrical resistivity and conductivity

The resistivity of different materials varies by an enormous amount: For example, the conductivity of teflon is about $10^{30}$ times lower than the conductivity of copper. Why is there such a difference? Loosely speaking, a metal has large numbers of "delocalized" electrons that are not stuck in any one place, but free to move across large distances, whereas in an insulator (like teflon), each electron is tightly bound to a single molecule, and a great force is required to pull it away. Semiconductors lie between these two extremes. More details can be found in the article: Electrical resistivity and conductivity. For the case of electrolyte solutions, see the article: Conductivity (electrolytic).

Resistivity varies with temperature. In semiconductors, resistivity also changes when light is shining on it. These are discussed below.

[edit] Measuring resistance

Main article: ohmmeter

An instrument for measuring resistance is called an ohmmeter. Simple ohmmeters cannot measure low resistances accurately because the resistance of their measuring leads causes a voltage drop that interferes with the measurement, so more accurate devices use four-terminal sensing.
**[edit] Typical resistances**

See also: *Electrical resistivities of the elements (data page)* and *Electrical resistivity and conductivity*

<table>
<thead>
<tr>
<th>Component</th>
<th>Resistance ($\Omega$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 meter of copper wire with 1mm diameter</td>
<td>0.02[4]</td>
</tr>
<tr>
<td>1 km overhead power line (typical)</td>
<td>0.03[5]</td>
</tr>
<tr>
<td>AA battery (typical internal resistance)</td>
<td>0.1[6]</td>
</tr>
<tr>
<td>Incandescent light bulb filament (typical)</td>
<td>200-1000[7]</td>
</tr>
<tr>
<td>Human body</td>
<td>1000 to 100,000[8]</td>
</tr>
</tbody>
</table>

**[edit] Static and differential resistance**

The IV curve of a non-ohmic device (purple). Point A represents the current and voltage values right now. The static resistance is the inverse slope of line B through the origin. The differential resistance is the inverse slope of tangent line C.

The IV curve of a component with negative differential resistance, an unusual phenomenon where the IV curve is non-monotonic. See also: *Small-signal model*

Many electrical elements, such as diodes and batteries do not satisfy Ohm’s law. These are called non-ohmic or nonlinear, and are characterized by an I–V curve which is not a straight line through the origin.
Resistance and conductance can still be defined for non-ohmic elements. However, unlike ohmic resistance, nonlinear resistance is not constant but varies with the voltage or current through the device; its operating point. There are two types:

- **Static resistance** (also called *chordal* or *DC resistance*) - This corresponds to the usual definition of resistance; the voltage divided by the current

\[ R_{\text{static}} = \frac{v}{i}. \]

It is the slope of the line (chord) from the origin through the point on the curve. Static resistance determines the power dissipation in an electrical component. Points on the IV curve located in the 2nd or 4th quadrants, for which the slope of the chordal line is negative, have *negative static resistance*. Passive devices, which have no source of energy, cannot have negative static resistance. However active devices such as transistors or op-amps can synthesize negative static resistance with feedback, and it is used in some circuits such as gyrotrons.

- **Differential resistance** (also called *dynamic*, *incremental* or *small signal resistance*) - Differential resistance is the derivative of the voltage with respect to the current; the slope of the IV curve at a point

\[ R_{\text{diff}} = \frac{dv}{di}. \]

If the IV curve is non-monotonic (with peaks and troughs), the curve will have a negative slope in some regions; so in these regions the device has *negative differential resistance*. Devices with negative differential resistance can amplify a signal applied to them, and are used to make amplifiers and oscillators. These include tunnel diodes, Gunn diodes, IMPATT diodes, magnetron tubes, and unijunction transistors.

[edit] AC circuits

[edit] Impedance and admittance
The voltage (red) and current (blue) versus time (horizontal axis) for a capacitor (top) and inductor (bottom). Since the amplitude of the current and voltage sinusoids are the same, the absolute value of impedance is 1 for both the capacitor and the inductor (in whatever units the graph is using). On the other hand, the phase difference between current and voltage is -90° for the capacitor; therefore, the complex phase of the impedance of the capacitor is -90°. Similarly, the phase difference between current and voltage is +90° for the inductor; therefore, the complex phase of the impedance of the inductor is +90°.

Main articles: Electrical impedance and Admittance

When an alternating current flows through a circuit, the relation between current and voltage across a circuit element is characterized not only by the ratio of their magnitudes, but also the difference in their phases. For example, in an ideal resistor, the moment when the voltage reaches its maximum, the current also reaches its maximum (current and voltage are oscillating in phase). But for a capacitor or inductor, the maximum current flow occurs as the voltage passes through zero and vice-versa (current and voltage are oscillating 90° out of phase, see image at right). Complex numbers are used to keep track of both the phase and magnitude of current and voltage:

\[ V(t) = \text{Re}(V_0 e^{j\omega t}), \quad I(t) = \text{Re}(I_0 e^{j\omega t}), \quad Z = \frac{V_0}{I_0}, \quad Y = \frac{I_0}{V_0} \]

where:

- \( t \) is time,
- \( V(t) \) and \( I(t) \) are, respectively, voltage and current as a function of time,
- \( V_0, I_0, Z, \) and \( Y \) are complex numbers,
- \( Z \) is called impedance,
- \( Y \) is called admittance,
- \( \omega \) is the angular frequency of the AC current,
- \( j = \sqrt{-1} \) is the imaginary unit.

The impedance and admittance may be expressed as complex numbers which can be broken into real and imaginary parts:

\[ Z = R + jX, \quad Y = G + jB \]

where \( R \) and \( G \) are resistance and conductance respectively, \( X \) is reactance, and \( B \) is susceptance. For ideal resistors, \( Z \) and \( Y \) reduce to \( R \) and \( G \) respectively, but for AC networks containing capacitors and inductors, \( X \) and \( B \) are nonzero.

\[ Z = 1/Y \] for AC circuits, just as \( R = 1/G \) for DC circuits.

[edit] Frequency dependence of resistance
Another complication of AC circuits is that the resistance and conductance can be frequency-dependent. One reason, mentioned above is the skin effect (and the related proximity effect). Another reason is that the resistivity itself may depend on frequency (see Drude model, deep-level traps, resonant frequency, Kramers–Kronig relations, etc.)

[edit] Energy dissipation and Joule heating

Running current through a resistance creates heat, in a phenomenon called Joule heating. In this picture, a cartridge heater, warmed by Joule heating, is glowing red hot. Main article: Joule heating

Resistors (and other elements with resistance) oppose the flow of electric current; therefore, electrical energy is required to push current through the resistance. This electrical energy is dissipated, heating the resistor in the process. This is called Joule heating (after James Prescott Joule), also called ohmic heating or resistive heating.

The dissipation of electrical energy is often undesired, particularly in the case of transmission losses in power lines. High voltage transmission helps reduce the losses by reducing the current for a given power.

On the other hand, Joule heating is sometimes useful, for example in electric stoves and other electric heaters (also called resistive heaters). As another example, incandescent lamps rely on Joule heating: the filament is heated to such a high temperature that it glows "white hot" with thermal radiation (also called incandescence).

The formula for Joule heating is:

\[ P = I^2 R \]

where \( P \) is the power (energy per unit time) converted from electrical energy to thermal energy, \( R \) is the resistance, and \( I \) is the current through the resistor.

[edit] Dependence of resistance on other conditions

[edit] Temperature dependence

Main article: Electrical resistivity and conductivity#Temperature dependence
Near room temperature, the resistivity of metals typically increases as temperature is increased, while the resistivity of semiconductors typically decreases as temperature is increased. The resistivity of insulators and electrolytes may increase or decrease depending on the system. For the detailed behavior and explanation, see Electrical resistivity and conductivity.

As a consequence, the resistance of wires, resistors, and other components often change with temperature. This effect may be undesired, causing an electronic circuit to malfunction at extreme temperatures. In some cases, however, the effect is put to good use. When temperature-dependent resistance of a component is used purposefully, the component is called a resistance thermometer or thermistor. (A resistance thermometer is made of metal, usually platinum, while a thermistor is made of ceramic or polymer.)

Resistance thermometers and thermistors are generally used in two ways. First, they can be used as thermometers: By measuring the resistance, the temperature of the environment can be inferred. Second, they can be used in conjunction with Joule heating (also called self-heating): If a large current is running through the resistor, the resistor's temperature rises and therefore its resistance changes. Therefore, these components can be used in a circuit-protection role similar to fuses, or for feedback in circuits, or for many other purposes. In general, self-heating can turn a resistor into a nonlinear and hysteretic circuit element. For more details see Thermistor#Self-heating effects.

If the temperature $T$ does not vary too much, a linear approximation is typically used:

$$R(T) = R_0 [1 + \alpha (T - T_0)]$$

where $\alpha$ is called the temperature coefficient of resistance, $T_0$ is a fixed reference temperature (usually room temperature), and $R_0$ is the resistance at temperature $T_0$. The parameter $\alpha$ is an empirical parameter fitted from measurement data. Because the linear approximation is only an approximation, $\alpha$ is different for different reference temperatures. For this reason it is usual to specify the temperature that $\alpha$ was measured at with a suffix, such as $\alpha_{15}$, and the relationship only holds in a range of temperatures around the reference.\[9\]

The temperature coefficient $\alpha$ is typically $+3 \times 10^{-3}$ K$^{-1}$ to $+6 \times 10^{-3}$ K$^{-1}$ for metals near room temperature. It is usually negative for semiconductors and insulators, with highly variable magnitude.\[10\]

[edit] Strain dependence

Main article: Strain gauge

Just as the resistance of a conductor depends upon temperature, the resistance of a conductor depends upon strain. By placing a conductor under tension (a form of stress that leads to strain in the form of stretching of the conductor), the length of the section of conductor under tension increases and its cross-sectional area decreases. Both these effects contribute to increasing the resistance of the strained section of conductor. Under compression (strain in the opposite
direction), the resistance of the strained section of conductor decreases. See the discussion on
strain gauges for details about devices constructed to take advantage of this effect.

[edit] Light illumination dependence

Main articles: Photoresistor and Photoconductivity

Some resistors, particularly those made from semiconductors, exhibit photoconductivity,
meaning that their resistance changes when light is shining on them. Therefore they are called
photoresistors (or light dependent resistors). These are a common type of light detector.

[edit] Superconductivity

Main article: Superconductivity

Superconductors are materials that have exactly zero resistance and infinite conductance,
because they can have V=0 and I≠0. This also means there is no joule heating, or in other words
no dissipation of electrical energy. Therefore, if superconductive wire is made into a closed loop,
current will keep flowing around the loop forever. Superconductors require cooling to
temperatures near 4 K with liquid helium for most metallic superconductors like NbSn alloys, or
cooling to temperatures near 77K with liquid nitrogen for the expensive, brittle and delicate
ceramic high temperature superconductors. Nevertheless, there are many technological
applications of superconductivity, including superconducting magnets.

[edit] See also

Electronics portal

- Electrical measurements
- Resistor
- Electrical conduction for more information about the physical mechanisms for
  conduction in materials.
- Voltage divider
- Voltage drop
- Thermal resistance
- Sheet resistance
- SI electromagnetism units
- Quantum Hall effect, a standard for high-accuracy resistance measurements.
- Series and parallel circuits
- Johnson–Nyquist noise

[edit] References


4. The resistivity of copper is about $1.7 \times 10^{-8} \Omega m$. See [1].

5. ^ [2] ^ Electric power substations engineering by John Douglas McDonald, p 18-37, google books link

6. ^a^ A 60W light bulb in the USA (120V mains electricity) draws RMS current $60W/120V=500mA$, so its resistance is $120V/500mA=240$ ohms. The resistance of a 60W light bulb in Europe (230V mains) would be 900 ohms. The resistance of a filament is temperature-dependent; these values are for when the filament is already heated up and the light is already glowing.

7. ^a^ For a fresh Energizer E91 AA alkaline battery, the internal resistance varies from 0.9$\Omega$ at -40°C, to 0.1$\Omega$ at +40°C.

8. ^a^ A 60W light bulb in the USA (120V mains electricity) draws RMS current $60W/120V=500mA$, so its resistance is $120V/500mA=240$ ohms. The resistance of a 60W light bulb in Europe (230V mains) would be 900 ohms. The resistance of a filament is temperature-dependent; these values are for when the filament is already heated up and the light is already glowing.


Piezoresistive effect

The piezoresistive effect describes change in the electrical resistivity of a semiconductor when mechanical stress is applied. In contrast to the piezoelectric effect, the piezoresistive effect only causes a change in electrical resistance, not in electric potential.

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- **1 History**
- **2 Mechanism**
  - 2.1 Resistance change in metals
  - 2.2 Piezoresistive effect in semiconductors
    - 2.2.1 Piezoresistive effect in silicon
- **3 Piezoresistive silicon devices**
  - 3.1 Piezoresistors
    - 3.1.1 Fabrication
    - 3.1.2 Physics of operation
  - 3.2 Other piezoresistive devices
- **4 References**
- **5 See also**

[edit] History

The change of electrical resistance in 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).

[edit] Mechanism

In semiconductors, changes in inter-atomic spacing resulting from strain affects the bandgaps making it easier (or harder depending on the material and strain) for electrons to be raised into the conduction band. This results in a change in resistivity of the semiconductor. Piezoresistivity is defined by
\[ \rho_\sigma = \left( \frac{\partial \rho}{\rho} \right) \varepsilon \]

Where

\[ \partial \rho = \text{Change in resistivity} \]
\[ \rho = \text{Original resistivity} \]
\[ \varepsilon = \text{Strains} \]

Piezoresistivity has a much greater effect on resistance than a simple change in geometry and so a semiconductor can be used to create a much more sensitive strain gauge, though they are generally also more sensitive to environmental conditions (esp. temperature).

[edit] Resistance change in metals

This section's factual accuracy is disputed. (February 2011)

The resistance change in metals is only due to the change of geometry resulting from applied mechanical stress and can be calculated using the simple resistance equation derived from ohm's law;

\[ R = \rho \frac{\ell}{A} \]

where

\[ \ell \text{ Conductor length [m]} \]
\[ A \text{ Cross-sectional area of the current flow [m}^2\text{]} \]

[edit] Piezoresistive effect in semiconductors

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

[edit] Piezoresistive effect in silicon

The resistance 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 to orders of magnitudes larger than those observed in metals (Smith 1954). 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 mobilities. This results in varying mobilities 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.

[edit] Piezoresistive silicon 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. Since 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 piezoresistive effect. Many commercial devices such as 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.

[edit] Piezoresistors

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.

[edit] Fabrication

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+ plus diffusions are necessary to facilitate ohmic contacts to the device.

Schematic cross-section of the basic elements of a silicon n-well piezoresistor.
Physics of operation

For typical stress values in the MPa range the stress dependent voltage drop along the resistor $V_r$, can be considered to be linear. A piezoresistor aligned with the x-axis as shown in the figure may be described by

$$V_r = R_0 I [1 + \pi_L \sigma_{xx} + \pi_T (\sigma_{yy} + \sigma_{zz})]$$

where $R_0$, $I$, $\pi_T$, $\pi_L$, and $\sigma_{ij}$ denote the stress free resistance, the applied current, the transverse and longitudinal piezoresistive coefficients, and the three tensile stress components, respectively. The piezoresistive coefficients vary significantly with the sensor orientation with respect to the crystallographic axes and with the doping profile. Despite the fairly large stress sensitivity of simple resistors, they are preferably used in more complex configurations eliminating certain cross sensitivities and drawbacks. Piezoresistors have the disadvantage of being highly sensitive to temperature changes while featuring comparatively small relative stress dependent signal amplitude changes.

Advanced stress sensors derived from piezoresistors are Wheatstone bridges, transducers, and picture frame sensors.

Other piezoresistive devices

In silicon the piezoresistive effect is used in piezoresistors, transducers, piezo-FETS, solid state accelerometers and bipolar transistors.

References


See also

- Piezoelectricity
- Electrical resistance