

Human hands Asbestos Tendency to gain Rabbit Fur **POSITIVE charge** Glass, Mica Human Hair Nylon, Wool Lead Silk Aluminum Paper Cotton Steel Wood Amber Hard Rubber Mylar Nickel, Copper Silver, Brass Gold, Platinum Polyester, Celluloid Saran Wrap Polvurethane Polyethylene Tendency to gain Polypropylene **NEGATIVE charge** Vinyl, Silicon Teflon Silicon Rubber

Triboelectric effect

A triboelectric effect is a result of a mechanical charge redistribution.

For instance, rubbing a glass rod with silk strips off electrons from the surface of the rod, thus leaving an abundance of positive charges, i.e., giving the rod a positive charge. It should be noted that the electric charge is conserved: it is neither created nor destroyed. Electric charges can be only moved from one place to another. Giving negative charge means taking electrons from one object and placing them onto another (charging it negatively). The object, which loses some amount of electrons, is said gets a positive charge.

A triboelectric effect influences an extremely small number of electrons as compared with the total electronic charge in an object. Actual amount of charges in any object is very large.

https://www.youtube.com/watch?v=IDQYakHRAG8

Isolators, semiconductors and conductors



With respect to electric charges, there are three kinds of materials: **isolators**, **semiconductors**., **conductors**. In conductors, electric charges (electrons) are free to move through the material, whereas in isolators they are not. Although there is no perfect isolator, the isolating ability of fused quartz is about 10²⁵ times as great as that of copper, so that for practical purposes many materials are considered perfect isolators. The semiconductors are intermediate between conductors and isolators in their ability to conduct electricity. Among the elements, silicon and germanium are well-known examples. In semiconductors, the electrical conductivity may be greatly increased by adding small amounts of other elements, traces of arsenic or boron are often added to silicon for this purpose. For the sensing technologies, semiconductors are very interesting materials because their ability to conduct electricity can be manipulated by applying external inputs, like electric and magnetic fields and light.

Electrical field and potential



If a small positive electric test charge q_0 is positioned in the vicinity of a charged object, it will be subjected to a repelling electric force. If we place a negative charge on the object, it will attract the test charge. In a vector form, the repelling (or attracting) force is shown as **f**. A fact that the test charge is subjected to force without a physical contact between charges means that the volume of space which is occupied by the test charge may be characterized by a so-called *electric field*.

Electrical field
$$\vec{E} = \frac{\vec{F}}{q} = \frac{1}{4\pi\epsilon_0} \frac{q_1}{r} \vec{r}$$

The formula expresses an electric field as a force divided by a property of a test charge. The test charge must be very small not to disturb the electric field. Ideally, it should be infinitely small, however, since the charge is quantized, we cannot contemplate a free test charge whose magnitude is smaller than the electronic charge: $e=1.602 \times 10^{-19}$ C.



Vector Field Flux

 $\vec{A} \cdot d\vec{S} = \int \vec{A} \cdot \vec{n} dS$

II

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 $\vartheta = 90^0$



 $\vartheta = 180^{0}$





Gauss' law

 \vec{E}

 \vec{n}

$$\Phi = \int_{S} \vec{E} \cdot d\vec{S} = \int_{S} \vec{E} \cdot \vec{n} dS = \frac{Q}{\epsilon_{0}}$$

 $\Phi = flux$

$$\vec{E} = electric field \left[\frac{N}{C}\right]$$

 $\epsilon_0 = 8.8541878 \cdot 10^{-12} \frac{C^2}{Nm^2}$ vacuum permittivity constant

 $d\vec{S}$ infinitesimal vector area [m²]

Gauss' law

 $=\frac{\rho a}{3\varepsilon_0}$

inside

Spherically symmetrical charge distribution

$$\Phi_s = \oint \vec{E} \cdot d\vec{S} = \frac{Q}{\epsilon_0}$$

$$Q = \sigma^+ \frac{4}{3}\pi a^3 \implies r \ge a \qquad E = \frac{\sigma^+}{3\epsilon_0} \frac{a^3}{r^2}$$



r а Cause of the repelling forces between charges of the same sign, all charges try to move as far as possible from one another. The only way to do this is to move to the foremost distant place in the material, which is the outer surface. Of all places on the outer surface the most preferable places are the areas with the highest curvatures.

outside

Gauss' law

Infinite charged line



$$\Phi_{s} = \oint \vec{E} \cdot d\vec{S} = \frac{Q}{\epsilon_{0}}$$
$$E2\pi r \Delta z = \frac{\lambda^{+} \Delta z}{\epsilon_{0}}$$
$$E = \frac{\lambda^{+}}{2\pi \epsilon_{0} r}$$





$$\Phi_{s} = \oint \vec{E} \cdot d\vec{S} = \frac{Q}{\epsilon_{0}}$$

$$\frac{Q}{\epsilon_{0}} = \frac{\sigma^{+}\pi a^{2}}{\epsilon_{0}}$$

$$\Phi_{s} = \oint \vec{E} \cdot d\vec{S} = 2ES + 0 = 2E\pi a^{2}$$

$$E = \frac{\sigma^{+}}{2\epsilon_{0}}$$



Capacitance



Two isolated conductive plates are connect to the opposite poles of a battery, The plates will receive equal amounts of opposite charges. That is, a negatively charged plate will receive additional electrons while there will be a deficiency of electrons in the positively charged plate. Once disconnect the battery, the plates will remain charged theoretically infinitely long in vacuum. This is a so-called capacitor.

 $\frac{Q}{V} = C \ [F]$

C depends on the shapes, on the relative position of the plates and on the medium in which the plates are immersed. The SI unit for capacitance is $1F = \frac{1C}{1V}$ which is represented by the abbreviation F. A farad is a very large capacitance, hence, in practice submultiples of the farad are generally used.



A capacitive sensor one needs a bad capacitor; traditionally all electronic components are fabricated as insensitive as possible to any environmental influences. In a capacitive sensor, capacitance is modulated (modified) by an external stimulus or by a signal from an intermediate transducer. **Thus, to vary capacitance, the stimulus needs to change one of the parameters that define the capacitance.**



Dielectrics

In 1837, Michael Faraday first investigated the effect of completely filling the space between the plates with a dielectric. He had found that the effect of the filling is to increase the capacitance of the device by a factor of κ , which is known as the dielectric constant of the material.

The increase in capacitance due to the dielectric presence is a result of molecular polarization. In some dielectrics (for instance, in water), molecules have a permanent dipole moment, while in other dielectrics, molecules become polarized only when an external electric field is applied. Such polarization is called induced. In both cases, either permanent electric dipoles or those acquired by induction tend to align molecules with an external electric field. This process is called dielectric polarization.

$$\vec{E} = \vec{E}_0 - \vec{E}' \qquad V = \frac{V_0}{k} \qquad C = k \frac{Q}{\Delta V} = kC_0$$

$$\boxed{C = k \frac{Q}{\Delta V} = k\varepsilon_0 \frac{A}{d} = k\varepsilon_0 G}$$
Dielectric constants must be excited for a test for

[k]

85

80

75

70

65

0 10 20 30 40 50 60 70 80 90 100 [°C]

Dielectric constants must be specified for a test frequency and temperature. Some dielectrics have a very uniform dielectric constant over a broad frequency range (for instance, polyethylene), while others display strong negative frequency dependence, that is, a dielectric constant decreases with frequency. Temperature dependence is also negative, the figure show κ for water as function of temperature.





Magnetism and electricity

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Hans Christian Ørsted (1777-1851 DK) Stationary electric charges make no effect on a magnetic compass (a compass needle is used as a tiny test magnet). It is clear that the moving electric charges were the cause of the magnetic field.

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It can be shown that magnetic field lines around a wire are circular and their direction depends on the direction of electric current, i.e., moving electrons Above and below the wire, magnetic field lines are pointed in the opposite direction. That is why the compass needle turns around when it is placed below the wire.

Magnetism and electricity



A fundamental property of magnetism is that moving electric charges (electric current) essentially produce a magnetic field. Knowing this, Albert Einstein came up with explanation of the nature of a permanent magnet. A simplified model of a magnetic field origination process is shown in the figure. An electron continuously spins in an eddy motion around the atom. The electron movement constitutes a circular electric current around the atomic nucleus. That current is a cause for a small magnetic field. In other words, a spinning electron forms a permanent magnet of atomic dimensions.



Michael Faraday (1791-1867 UK)

Faraday law

If an electric charge is moved across a magnetic field, a deflecting force is acting on that charge. It must be emphasized that it is not important what actually moves, either the charge or the source of the magnetic field. **What matters is a relative displacement of those**. A discovery that a moving electric charge can be deflected as a result of its interaction with the magnetic field is a fundamental in electromagnetic theory. Deflected electric charges result in an electric field generation, which, in turn, leads to a voltage difference in a conducting material, thus producing an electric current



A sideways deflecting force F acts on the charge. By sideways we mean that \vec{F} is at a right angle to \vec{v} . It is interesting to note that vector \vec{v} changes its direction while moving through the magnetic field. This results in a spiral rather than parabolic motion of charge. The the spiral movement is cause for а а magnetoresistive effect, which forms a foundation for the magnetoresistive sensors.



magnetoresistor Α shown in the figure is placed in magnetic field \vec{B} and supplied with constant electric current i. The swirling electronic path reflects in change of the resistance, thus a known current, for voltage across the resistor represents strength of the magnetic field. The reason why the resistance goes up is a longer path for electrons to travel inside the material, thus experience а higher resistance to their travel.

https://youtu.be/ZVqTt5g6Uqc

Permanent Magnets

Permanent magnets are useful components for fabricating magnetic sensors for detection of motion, displacement, position, proximity, etc. To select the magnet for any particular application, the following characteristics should be considered:

- Residual inductance (B) in gauss or millitesla (mT): how strong the magnet is ?
- Coercive force (H) in Oersteds (Oe) or kA/m: how well will the magnet resist external demagnetization forces? (1 Oe = 0.08 kA/m).
- Maximum energy product, MEP, (BH_{max}). A 10⁶ gauss-oersted, indicated as MGOe (mega-gauss-oersted), is 7.96 kJ/m³ A strong magnet that is also very resistant to demagnetization forces has a high MEP. Magnets with higher MEP are better, stronger, and more expensive.
- Temperature coefficient in %/ C shows how much B changes with temperature.

Magnets are produced from special alloys. Examples are rare earth (e.g., samarium)-cobalt alloys. These are the best magnets, however, they are too hard for machining, and must be ground if shaping is required. Their maximum MEP is about 16×10⁶ or 16MGOe. Another popular alloy is Alnico, which contains aluminium, nickel, cobalt, iron, and some additives. These magnets can be cast, or sintered by pressing metal powders in a die and heating them. Sintered Alnico is well suited to mass production.

Permanent Magnets

Ceramic magnets contain barium or strontium ferrite (or another element from that group) in a matrix of a ceramic material that is compacted and sintered. They are poor conductors of heat and electricity, chemically inert, and have high value of H. Another alloy for the magnet fabrication is **Cunife**, which contains copper, nickel, and iron. It can be stamped, swaged, drawn, or rolled into final shape. Its MEP is about 1.4×10⁶. **Iron-chromium magnets** are soft enough to undergo machining before the final aging treatment hardens them. Their maximum MEP 6

is 5.25×10^6 . Plastic and rubber magnets consist of barium or strontium ferrite in a plastic matrix material. They are very inexpensive and can be fabricated in many shapes. Their maximum MEP is about 1.2×10^6 .

A **neodymium magnet** (also known as NdFeB, NIB, or Neo magnet), a type of rare-earth magnet, is a permanent magnet made from an alloy of neodymium, iron, and boron to form the Nd₂Fe₁₄B tetragonal crystalline structure. *This material is currently the strongest type of permanent magnet*. In practice, the magnetic properties of Neodymium magnets depend on the alloy composition, microstructure, and manufacturing technique employed. Neodymium magnets have very much higher coercivity and energy product, but lower Curie temperature than other types of magnets.

In the 1990s it was discovered that certain molecules containing paramagnetic metal ions are capable of storing a magnetic moment at very low temperatures. In fact, these magnets are large molecules with strong magnetic properties. Such magnets are called single molecule magnets (SMM). Most SMM's contain manganese, but can also be found with vanadium, iron, nickel, and cobalt clusters.

Advantages of SMMs include strong residual inductance, solubility in organic solvents, and sub-nanoscale dimensions. More recently it has been found that some chain systems can also display a magnetization which persists for long times at relatively higher temperatures. These systems have been called single-chain magnets (SCM).

Coil and solenoid



The solenoid magnetic field is the vector sum of the fields' setup by all the turns that make up the solenoid:

A solenoid and coil are made in form of a long wire wound in helix and carrying current i. Solenoids and coils are practical devices for producing magnetic fields. Solenoids are often used as actuators for converting electric currents to mechanical forces. But they also are the basis for many useful sensors, especially for detecting movement and proximity.

> The difference between a coil and solenoid is that the former may have any loopy shape, while the latter is a tightly packet coil in form of a cylinder. In the following discussion we assume that a solenoid is very long as compared with its diameter. The solenoid magnetic field is the vector sum of the fields' setup by all the turns that make up the solenoid.

$$\vec{B} = \mu_0 \frac{N}{l}i$$



Manu Balakrishnan , Navaneeth Kumar N Detection of Plunger Movement in DC Solenoids Texas Instruments

The plunger movement induces back EMF in the solenoid coil and this causes a brief reduction in the solenoid current. At point **2**, the plunger has moved completely and the current gets reduced to I_{VALLEY} . After complete movement of the plunger, the solenoid current continues to rise until it reaches its maximum level limited by the coil DC resistance.

In 1831, Michael Faraday in England and Joseph Henry in the U.S.A. discovered one of the most fundamental effects of electromagnetism: an ability of a varying magnetic field to induce electric current in a wire. Magnetic field is nonspecific in its origin, so it is not important how the field is produced (e.g. by a permanent magnet or by a solenoid) the effect is the same. **Electric current is generated as long as the magnetic field changes**. A stationary magnetic field produces no current.

Faraday's law of induction says that the induced voltage, or electromotive force (EMF), is equal to the rate at which the magnetic flux through the circuit changes. If the rate of change is in Wb/s, the EMF. will be in volts:

$$\varepsilon = -\frac{d\Phi_B(t)}{dt} = -\frac{d}{dt} \int_{S} \vec{B} \cdot d\vec{S}$$

The minus sign is an indication of the direction of the induced EMF. If varying magnetic flux is applied to a solenoid, EMF. appears in every turn and all these EMF's must be added up. If a coil is wound in such a manner as each turn has the same cross-sectional area, the flux through each turn will be the same, then the induced voltage is

$$\varepsilon = -N \frac{d\Phi_B(t)}{dt} = -N \frac{d}{dt} \int \vec{B} \cdot d\vec{S}$$

The equation means that voltage in a pick-up circuit can be produced by either changing amplitude of magnetic field (B) or changing area of the circuit (S). Thus, induced voltage depends on:

- Moving the source of magnetic field (magnet, coil, wire, etc.) with respect to a receiving coil.
- Varying current in the coil or wire, which produces the magnetic field.
- Changing orientation of the magnetic source with respect to the pick-up circuit.
- Changing geometry of a pick-up circuit, for instance, by stretching it or squeezing, or changing the number of turns in a coil.

If electric current passes through a coil, which is situated in close proximity with another coil, according to *Faraday's law*, a EMF in the second coil will appear. However, **the magnetic field penetrates not only the second coil, but the first coil as well**. Thus, the magnetic field sets EMF in the same coil where it is originated. This is called self-induction and the resulting voltage is called a **self-induced EMF** The Faraday's law for a central portion of a solenoid is

$$\varepsilon_{1(1)} = -\frac{d}{dt}\phi_{1(1)} = -N_1\frac{d}{dt}\int \vec{B}_1 \cdot d\vec{S} = N_2 = -\mu_0\frac{(N_1)^2}{l}\pi r_1^2\frac{d}{dt}i_1$$

$$z$$

$$\varepsilon_{2(1)} = -\frac{d}{dt}\phi_{2(1)} = -N_2\frac{d}{dt}\int \vec{B}_1 \cdot d\vec{S} = N_2 = -\mu_0\frac{N_1N_2}{l}\pi r_1^2\frac{d}{dt}i_1$$

$$\varepsilon_{1(1)} = -\frac{d}{dt}\phi_{1(1)} = -N_1 \frac{d}{dt} \int \vec{B}_1 \cdot d\vec{S} = N_2 = -\mu_0 \frac{(N_1)^2}{l} \pi r_1^2 \frac{d}{dt} i_1$$

$$\varepsilon_{1(1)} = -L_{11} \frac{d}{dt} i_1 \qquad \qquad L_{11} = \mu_0 \frac{N_1^2}{l} \pi r_1^2 = \mu_0 \frac{N_1^2}{l^2} l \pi r_1^2 = \mu_0 n^2 l \pi r_1^2 = \mu_0 n^2 G$$

Inductance

- Induced voltage is proportional to the rate of change in current through the inductor.
- Voltage is essentially zero for dc.
- Voltage increases linearly with the current rate of change.
- Voltage polarity is different for increased and decreased currents flowing in the same direction.
- Induced voltage is always in the direction that opposes the change in current.

If a magnetic core is inserted into the inner space of the solenoid, inductance will depend on two additional factors: the relative magnetic permeability, μ_r , of the core material, and g, the core geometry factor, g:

Note that factor g depends on size and shape of the magnetic core, its depth of insertion, and closeness to the ends of the solenoid. Another point that should be considered is that relative permeability μ_r of a ferromagnetic material changes with current i_1 , thus the equation needs a correction coefficient η_i that is function of the current passing through the solenoid coil having a magnetic core (with no core $\mu_r = \eta_i = 1$): $I_{11} = \mu_0 \mu_r \eta_i n^2 gG$ Inductance



This equation suggest that inductance L can be modulated by every factor at its right side (except μ_0 that is a universal constant): the number of the coil turns can vary, all dimensions of the coil can be changed, the core shape and depth of insertion can be changed, and even the core material can be modified. This makes the inductive sensors very useful in many applications, for example to measure displacement for detecting force, pressure, position, and other variables.





Lenz law

In many sensor applications involving inductive coupling, one should always consider that current induced in the secondary coil produces its own magnetic field that works backward toward the primary coil. This phenomenon is known as Lenz Law that states: **The induced current will appear in such a direction that it opposes the current that produced it**. The minus sign in the Faraday law suggests this opposition. Thus, the induced current tends to reduce the originating current in the primary coil. It can be said that Lenz Law is similar to Newton's third law of motion (i.e., to every action there is always an equal and opposite reaction). Lenz's law refers to induced currents, which means that it applies only in closed conduction circuits. Note that the opposing magnetic flux in a coil reduces it inductance. Lenz law has a very broad range of applications, including **electromagnetic braking**, **induction cooktops**, **metal detectors**, and many others.

https://www.youtube.com/watch?v=GMP14t9mgrc

Eddy current

Eddy current is an electrical phenomenon discovered in 1851 by French physicist Le on Foucault. Thus, this current sometimes is called Foucault current. It appears in two cases:

- when a conductor is exposed to a changing magnetic field due to relative motion of the field source and conductor,
- due to changing intensity of the magnetic field.

These effects cause a circulating flow of electrons, or a circular current, within the body of the conductor. The conductor may be magnetic or not. The eddy currents circulate in the plains that are perpendicular to the magnetic flux. If they are induced by a coil, they normally travel parallel to the coil's winding and the flow is limited to the area of the inducing magnetic field. Eddy currents concentrate near the surface adjacent to an excitation coil and their strength decreases with distance from the coil. Eddy current density decreases exponentially with depth. This phenomenon is known as the skin effect.

These circulating eddies of current create induced magnetic fields that oppose the change of the original magnetic field due to Lenz's law, thus causing repulsive or drag forces between the conductor and the magnet or the inducing coil. The stronger the applied magnetic field, or the greater the electrical conductivity of the conductor, or the faster the field that the conductor is exposed to changes, then the greater the currents that are developed and the greater the opposing field. The skin effect arises when the eddy currents flowing in the test object at any depth produce magnetic fields which oppose the primary field, thus reducing the net magnetic flux and causing a decrease in current flow as the depth increases. Alternatively, eddy currents near the surface can be viewed as shielding the coil's magnetic field, thereby weakening the magnetic field at greater depths and reducing induced currents.

https://www.youtube.com/watch?v=2tsVuf9pLOE

Resistance

In any material, electrons move randomly like gas in a closed container. There is no preferred direction and an average concentration of electrons in any part of material is uniform (assuming that the material is homogeneous). Let us take a bar of an arbitrary material. The length of the bar is L. When the ends of the bar are connected to the battery having voltage V electric field E will be setup within the material. It is easy to determine strength of the electric field:



The SI unit of current is ampere (A): 1 A = 1C / 1s. In SI, ampere is defined as electric current which is maintained in two infinitely long parallel wires separated by 1 m in free space, which produce a force between the two wires (due to their magnetic field) of $2 \cdot 10^{-7}$ N for each meter of length. An ampere is guite strong electric current. In sensor technologies, generally much smaller currents are used, therefore, submultiples of A are often employed.

Resistance

1 milliampere (mA)	10 ⁻³ A
1 microampere (µA)	10 ⁻⁶ A
1 nanoampere (nA)	10 ⁻⁹ A
1 picoampere (pA)	10 ⁻¹² A
1 femtoampere (fA)	10 ⁻¹⁵ A

No matter what the cross-section of the material is, whether it is homogeneous or not, the electric current through any cross-section is always the same for a given electric field. It is similar to a water flow through a combination of serially connected pipes of different diameters, the rate of flow is the same throughout of the pipe combination. The water flows faster in the narrow sections and slower in the wide section, but mount of water passing through any cross-section per unit of time is constant. The reason for that is very simple, water in the pipes is neither drained out, nor created. The same reason applies to electric current. One of the fundamental laws of physics is the law of conservation of charge. Under steady-state conditions, charge in a material is neither created nor destroyed. Whatever comes in must go out.

A conducting material, say a copper wire, can be modelled as a semirigid spring-like periodic lattice of positive copper ions. They are coupled together by strong electromagnetic forces. Each copper atom has one conduction electron, which is free to move about the lattice. When electric field E is established within the conductor, force - eE acts on each electron. The electron accelerates under the force and moves.

Resistance

However, the movement is very short as the electron collides with the neighbouring copper atoms, which constantly vibrate with intensity that is determined by the material temperature. The electron transfers its kinetic energy to the lattice and is often captured by the positive ion. When captured, it frees another electron, which keeps moving in the electric field until, in turn, it collides with the next portion of the lattice. The average time between collisions is designated as τ . It depends on the material type, structure, and impurities. For instance, at room temperature, a conduction electron in pure copper moves between collisions for an average distance of 0.04 µm with τ = 2.5 \cdot 10⁻¹⁴ s.


Specific resistivity

If we fabricate two geometrically identical rods from different materials, say from copper and glass, and apply to them the same voltage, the electric fields in the rods will be the same, but the resulting currents will be quite different. A material may be characterized by its ability to pass electric current. It is called resistivity and material is said to have electrical resistance that is defined by Ohm's law, meaning that a ratio of voltage to current is a constant:



$$R = \frac{V}{i}$$

Any material has electric resistivity and therefore is called a resistor. The SI unit of resistance is 1 ohm $(\Omega) = 1 \text{ V/1 A}.$

1 milliohm (mΩ)	10 ⁻³ Ω
1 Kilohm (k $oldsymbol{\Omega}$)	10 ³ Ω
1 Megaohm (k $oldsymbol{\Omega}$)	10 ⁶ Ω
1 Gigaohm (G $oldsymbol{\Omega}$)	10 ⁹ Ω

Specific resistivity

If we again compare electric current with water flow, pressure across the pipe line (in pascal) is analogous of voltage (V) across the resistor, electric current (C/s) is analogous of water flow (I/s), and electric resistance (Ω) corresponds to water flow resistance in the pipe (no special unit). It is clear that resistance to water flow is smaller when the pipe is short, wide, and has no obstructions. When the pipe has, for instance, a filter installed in it, resistance to water flow will be higher. Consider a human body where arterial blood flow may be restricted by cholesterol deposits on the inner lining of arteries. These deposits increase the flow resistance (called vascular resistance). The arterial blood pressure increases to compensate for rise in the vascular resistance, so the heart pumps stronger. If arterial pressure cannot keep-up with increase in the vascular resistance, the heart pumping force is no longer sufficient for providing a necessary blood flow to vital organs, including the heart itself. This may result in a heart attack or other complications.

The basic laws that govern the electric circuit designs are called Kirchhoff's Laws, after the German physicist Gustav Robert Kirchhoff (1824–1887). These laws were originally conceived by considering a similarity to the plumbing networks, which as we have seen, are analogous to the electric networks.



Gustav Robert Kirchhoff (1824–1887 DE) $\rho = \frac{E}{j} [\Omega m]$ $\rho = \frac{m}{ne^2 \tau}$ $R = \rho \frac{l}{a}$

As formulas establish the fundamental relationship between resistance and its parameters. Thus, if one wants to design a resistive sensor, she should find ways of modulating either the specific resistivity or geometry factor, I/a.



Temperature sensitivity of resistor

Metals have positive temperature coefficients (PTC) α , while many semiconductors and oxides have negative temperature coefficients of resistance (NTC). As a rule, the NTC resistors have high temperature nonlinearity.

When a conventional resistor is used in an electronic circuit, its resistance shall be as temperature independent as possible. A "good" resistor may have $\alpha = 10^{-5}$ or even lower. However, in sensing technologies, it is often desirable to have a "bad" resistor whose temperature coefficient of resistivity α is high and predictable.

A strong α allows fabricating two types of temperature sensors: one is known as a thermistor (a contraction of words thermal and resistor) and the other is a resistance temperature detector (RTD). The most popular RTD is a platinum (Pt) sensor that operates over a broad temperature range up to 600°C. The best-fit straight line is given by equation:



 $R(T) = R_0 (1 + 36.79 \cdot 10^{-4}T)\Omega$ $R(T) = R_0 (1 + 36.79 \cdot 10^{-4}T + 5.8 \cdot 10^{-7}T^2)\Omega$

Temperature sensitivity of resistor



Another type of the resistive temperature sensors includes thermistors that are resistors with large, either negative (NTC), or positive (PTC) temperature coefficients. For temperature measurements usually the NTC are employed, while the PTCs thermistors due to their very high nonlinearity are used for applications where a lesser accuracy is traded for a very high sensitivity in a selected region. The thermistors are ceramic semiconductors commonly made of oxides of one or more of the following metals: nickel, manganese, cobalt, titanium, iron. Oxides of other metals are occasionally used.

Temperature sensitivity of resistor

Resistances of thermistors vary from a fraction of an ohm to many Megohms. *Thermistors can be produced in form of disks, droplets, tubes, flakes, or thin films deposited on ceramic substrates.* Also, a thick-film paste can be printed on ceramic substrate to form a thick-film thermistor. Also resistance of a semiconductors (Ge and Si) may be controlled to create either NTC or PTC to form semiconductive RTDs and thermistors. Thermistors possess nonlinear temperature-resistance characteristics), which are generally approximated by one of several different equations. The most popular of the thermistor's transfer function approximations is the exponential form:



$$R_T = R_0 \cdot e^{\beta \left(\frac{1}{T} - \frac{1}{T_0}\right)}$$

 T_0 is the calibrating temperature;

 R_0 is its resistance at T_0 ;

 β is the thermistor material's characteristic temperature (β ranges between 2600 K and 4200 K).

Traditionally, in data sheets, thermistors are specified at a reference temperature of $t_0=25$ °C ($T_0=298.15$ K), while RTDs are specified at $t_0=0$ °C ($T_0=273.15$ K).

Strain sensitivity of a resistor

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Electrical resistance of a material changes when the material is mechanically deformed. Strain is a measure of the deformation. A mechanical deformation modulates either the specific resistivity or the geometry factor. The resistor's strain sensitivity is called the piezoresistivity from the Greek word π (corq (pressure). As we have seen before, a "good" resistor better be stable, while having a "bad" resistor gives us an opportunity to make a sensor. In this case, we are talking about a strain sensor that may be used to measure strain. Also it may serve as part in many other complex sensors, such as **displacement**, **force**, **pressure sensors**, etc.

$$\sigma = \frac{F}{A} = Y\frac{dl}{l} = Ye$$

Y is the young modulus of the material

$$R = \rho \frac{l}{a} = \rho \frac{l^2}{V}$$

Volume V of the material stays constant (no material is added or removed), while the length increases

$$\frac{dR}{dl} = 2\rho \frac{l}{V}$$

 S_e is the gauge factor or sensitivity (in metal 2 < S_e < 6.

Moister sensitivity of resistor

By selecting material for a resistor, one can control its specific resistivity and its susceptibility to environmental factors. One of the factors that may greatly affect p is the amount of moisture that can be absorbed by the resistor. A moisture-dependent resistor can be fabricated of a hygroscopic material whose specific resistivity is strongly influenced by concentration of the absorbed water molecules. This is a basis for the resistive humidity sensors that are called *hygristors*.

A typical resistive *hygristor* is comprised of a ceramic substrate that has two silk-screen printed conductive interdigitated electrodes. The electrodes are conductors where the space between them is covered by hygroscopic semi-conductive gel that forms a matrix to suspend conductive particles. This structure forms a resistor between two electrodes. The gel is typically fabricated of hydroxyethylcellulose, nonyl phenyl polyethylene glycol ether, and other organic materials with addition of carbon powder. The gel is thoroughly milled to produce a smooth mixture. Another type of a *hygristor* is fabricated of lithium chloride (LiCl) film and a binder. The coated substrates are cured under controlled temperature and humidity.

Resistance of the coating changes with humidity in a nonlinear way, which should be taken into account during calibration and data processing. The response time for many *hygristors* ranges from 10 to 30 s. It can be shortened in moving air. The resistance range varies from $1 \text{ k}\Omega$ to $100 \text{ M}\Omega$.

Hygristors are the active sensors, that is, they require an excitation signal to produce an electrical output. It is important to use only symmetrical AC excitation current with no DC bias to prevent polarization of the coating, otherwise the sensor will be destroyed.

Moister sensitivity of resistor









Piezoelectric effect

To pickup an electric charge, at least two conductive electrodes must be applied to the crystal at the opposite sides of the cut. As a result, a piezoelectric sensor becomes a capacitor with a dielectric material in-between the metal plates, where **the dielectric is a piezoelectric crystalline materia**. The dielectric acts as a generator of electric charge, resulting in voltage V across the capacitor.

It can be said that strain in the material charges the capacitor. A piezoelectric sensor is a direct converter mechanical stress into of a electricity. The piezoelectric effect is a reversible physical phenomenon. This means that stress produces electricity, while voltage applied across the crystal produces a mechanical strain, the material deformation.

Piezoelectric effect





A popular ceramic material for piezoelectric sensors is lead zirconium titanate (PZT) having formula $Pb(Zr,Ti)O_3$. The sensor manufacturing begins with high purity metal oxides (lead oxide, zirconium oxide, titanium oxide, etc.) in form of fine powders having various colors. The powders are milled to a specific fineness, and mixed thoroughly in chemically correct proportions. In a process called "calcining", the mixtures are then exposed to an elevated temperature, allowing the ingredients to react to form a powder, each grain of which has a chemical composition close to the desired final composition. At this stage, however, the grain does not have yet the desired crystalline structure.

The next step is to mix the calcined powder with solid and/or liquid organic binders (intended to burn out during firing) and mechanically form the mixture into a "cake" which closely approximates a shape of the final sensing element. To form the "cakes" of desired shapes, several methods can be used. Among them are pressing (under force of a hydraulic powered piston), casting (pouring viscous liquid into molds and allowing to dry), extrusion (pressing the mixture through a die, or a pair of rolls to form thin sheets), tape casting (pulling viscous liquid onto a smooth moving belt).

After the "cakes" have been formed, they are placed into a kiln and exposed to a very carefully controlled temperature profile. After burning out of organic binders, the material shrinks by about 15 %. The "cakes" are heated to a red glow and maintained at that state for some time, which is called the "soak time", during which the final chemical reaction occurs. The crystalline structure is formed when the material is cooled down. Depending on the material, the entire firing may take **24 h**.

When the material is cold, the contact electrodes are applied to its surface. This can be done by several methods. The most common of them are: a fired-on silver (a silk-screening of silver-glass mixture and refiring), an electroless plating (a chemical deposition in a special bath), and a sputtering (an exposure to metal vapor in a partial vacuum).

Crystallities (crystal cells) in the material can be considered electric dipoles. In some materials, like quartz, these cells are naturally oriented along the crystal axes, thus giving the material sensitivity to stress. In other materials, the dipoles are randomly oriented and the materials need to be "poled" to possess piezoelectric properties. To give a crystalline material the piezoelectric properties, several poling techniques can be used. The most popular poling process is a thermal poling, which includes the following steps:

 A crystalline material (ceramic or polymer film), which has randomly oriented dipoles, is warmed up slightly below its *Curie temperature*. In some cases (e.g., for a PVDF film) the material is stretched (strained) to give the crystals a predominant orientation. High temperature results in a stronger agitation of dipoles and permits to orient them more easily in a desirable direction.



- Material is placed in strong electric field, E, where dipoles align along the field lines. The alignment is not total. Many dipoles deviate from the field direction quite strongly, however, a statistically predominant orientation of the dipoles is maintained.
- The material is cooled down while the electric field across its thickness is maintained.



• The electric field is removed and the poling process is complete. As long as the poled material is maintained below the Curie temperature, its polarization remains permanent. The dipoles stay "frozen" in the direction, which was given to them by the electric field at high temperature.





The final operation includes cutting, machining, and grinding. After the piezo (pyro) element is prepared, it is installed into a sensor's housing, where its electrodes are bonded to the electrical terminals and/or other electronic components.

The final operation includes cutting, machining, and grinding. After the piezo element is prepared, it is installed into a sensor's housing, where its electrodes are bonded to the electrical terminals and/or other electronic components.

After poling, the crystal remains permanently polarized, with an electric charge formed at the electrodes for a relatively short time. There is a sufficient amount of free charge carriers, which move in the electric field setup inside the bulk material and there are plenty charged ions in the surrounding air. The charge carriers move toward the poled dipoles and neutralize their charges. Hence, after a while, the poled piezoelectric material becomes electrically discharged as long as it remains under steady-state conditions. When stress is applied, or air blows near its surface the balanced state is degraded and the piezoelectric material develops electric charges on its opposite surfaces. If the stress is maintained, the charges again will be neutralized by the internal leakage. **Thus, a piezoelectric sensor is responsive only to a changing stress rather than to a steady level of it**. In other words, a piezoelectric sensor is an AC device, rather than a DC. device.

Piezoelectric directional sensitivities (d coefficients) are temperature-dependent. For some materials (quartz), sensitivity drops with a slope of about -0.016 %/°C. For others (the PVDF films and ceramics) at temperatures below 40 °C it may go down, while at higher temperatures it increases with a raise in temperature. Nowadays, the most popular materials for fabrication piezoelectric sensors are ceramics. The earliest of the ferroelectric ceramics was barium titanite, a polycrystal-line substance having the chemical formula BaTiO₃. The stability of permanent polarization relies on the coercive force of the dipoles. In some materials, polarization may decrease with time. To improve stability of a poled material, impurities have been introduced into the basic material with the idea that the polarization may be "locked" into a position. While the piezoelectric constant changes with operating temperature, a dielectric constant, κ , exhibits a similar dependence. Thus, variations in these values tend to cancel each other as they are entered into numerator and denominator :this results in a better stability of the output voltage, V, over a broad temperature range.

The piezoelectric elements may be used as a single crystal, or in a multilayer form where several plates of the material are laminated together. This must be done with the electrodes placed in-between. Remember, a piezoelectric sensor is an AC device, so it will not respond to a constant or slowly changing force. When applied, of external force F is the part the an upper sensor expands. while the bottom compresses. If the layers are laminated correctly, this produces a double output signal.





The leakage resistors r are very large, on the orders of 10^{12} - 10^{14} Ω , meaning that the sensor has an extremely high output impedance. This requires special interface circuits, such as charge-to-voltage or current-to-voltage converters, or the voltage amplifiers with very high input resistances and very low input capacitances.

Zinc oxide was the first and most popular material for development of the **ultrasonic acoustic sensors**, **surface acoustic wave** (SAW) **devices**, **microbalances**, etc. One of its advantages is the ease of chemical etching in production of MEMS devices, in addition to the piezoelectric properties also it is pyroelectric The zinc oxide thin films are usually deposited on silicon by employing the sputtering technology.

Aluminum nitride, AIN, is an excellent piezoelectric material because of its high acoustic velocity and its endurance in humidity and high temperature. Its piezo-electric coefficient is somewhat lower than of ZnO but higher than of other thin-film piezoelectric materials, excluding ceramics. The high acoustic velocity makes it an attractive choice in the GHz frequency range.

Usually, the AIN thin films are fabricated by using the chemical vapor deposition (CVD) or reactive molecular beam epitaxy (MBE) technologies. However, the drawback of using these deposition methods is the need for high heating temperature (up to 1300 °C) of the substrate.

The **PZT** thin films possesses a larger piezoelectric coefficient than ZnO or AlN, and also a high pyroelectric coefficient, which makes it a good candidate for fabrication of **thermal radiation detectors**. A great variety of deposition techniques is available for the PZT, among which are the electron-beam evaporation, RF sputtering, ion-beam deposition, epitaxial growth by RF sputtering, magnetron sputtering, laser ablation, and sol-gel.

Pyroelectric material Pyroelectric material T_0 $T_1 > T_0$ $T_1 > T_0$

Thermal flux out

The pyroelectric materials are crystalline substances capable of generating an electrical charge in response to heat flow. The pyroelectric effect very closely relates to the piezoelectric effect. Like piezoelectrics, the pyroelectric materials are used in form of thin ceramic slices or films with the charge pick-up electrodes deposited on the T₀ opposite sides. A pyroelectric sensor is essentially a capacitor that can be electrically charged by thermal flux.



Even though there is no difference of the origin of heat, either from contacting a warm/cold surface, or by absorbing thermal radiation, the result is the same: **electric charge is generated**. The detector does not require any external electrical bias (excitation signal), thus it is a direct converter of a heat flow into electricity. It needs only an appropriate electronic interface circuit to measure the charge. **Pyroelectrics generate charge in response to a change in temperature**. Since a change in temperature essentially causes propagation of heat, a pyroelectric device is a heat flow detector rather than heat detector. When a pyroelectric crystal is exposed to a heat flow (for instance, from an infrared radiation source or from touching a warm or cold object), temperature of the exposed side is elevated and the side becomes a source or sink of heat which propagates through the pyroelectric material towards or from its opposite side. Hence, there is an outflow of heat from the crystal to the environment.

A crystal is considered to be pyroelectric if it exhibits a spontaneous temperature-dependent polarization. Of the 32 crystal classes, 21 are non-centrosymmetric and 10 of these exhibit pyroelectric properties. Beside the pyroelectric properties, all these materials exhibit piezoelectric properties as well: they generate electrical charge in response to mechanical stress. Thus, when a pyroelectric sensor is designed, it is very important to minimize all potential mechanical disturbances.

Pyroelectricity was observed for the first time in tourmaline crystals in the eighteenth century. Later, in the nineteenth century, Rochelle salt was used to make pyroelectric sensors. A large variety of materials became available after 1915: KDP (KH_2PO_4), ADP ($NH_4H_2PO_4$), BaTiO₃, and a composite of PbTiO₃ and PbZrO₃ known as PZT. *Presently, more than 1000 materials with a reversible polarization are known*.

The most important among them are triglycine sulphate (TGS) and lithium tantalite oxide (LiTaO₃). In 1969 H. Kawai discovered strong piezoelectricity in the plastic materials, polyvinylfluoride (PVF) and polyvinylidene fluoride (PVDF). These materials also posses substantial pyroelectric properties.



A pyroelectric material can be considered as a composition of a large number of minute crystallites, where each behaves as a small electric dipole. All these dipoles are randomly oriented. **Above a certain temperature, known as the Curie point, the crystallites have no dipole moment.** Manufacturing (poling) of pyroelectric materials is similar to that of the piezoelectrics.

There are several mechanisms by which changes in temperature will result in pyroelectricity. Temperature changes may cause:

- shortening of individual dipoles,
- · elongation of individual dipoles,
- Changes in the randomness of the dipole orientations due to thermal agitation.

These phenomena are called primary pyroelectricity.

There is also secondary pyroelectricity that, in a simplified way, may be described as a result of the piezoelectric effect, that is, development of strain in the material due to thermal expansion. At T_0 the piezoelectric sensor is homogeneous over its volume. That is, the sensor generates zero voltage across the electrodes. When the heat is applied to the top side of the sensor, in form of thermal (infrared) radiation, the radiation is absorbed by the heat-absorbing layer (e.g., goldblack or organic paint) and warms up the upper side of the pyroelectric material. As a result of the heat absorption, the upper side becomes warmer (the new warmer temperature is T_1) which causes the top side of the sensor to expand. The expansion leads to flexing (straining) of the crystalline material, which, in turn, produces stress and a change in a dipole orientation. Being a piezoelectric, the stressed material generates electric charges of the opposite polarities on the electrodes and thus a voltage is observed across the electrodes.



The dipole moment, M, of the bulk pyroelectric sensor is:

 $M = \mu A h$

µ= dipole moment per unit volumeA = sensor's areaH = sensor's thickness

The charge, Q_a , which can be picked up by the electrodes, develops the dipole moment across the material:



As the temperature varies, the dipole moment also changes, resulting in an induced charge. Thermal absorption may be related to a dipole change, so that μ must be considered as function of both temperature, T_a, and an incremental thermal energy, ΔW , absorbed by the material:

$$\Delta Q_a = A\mu(T_a, \Delta W)$$





The output signal from the pyroelectric sensor can be taken in form of either charge (current) or voltage, depending the on application. Being a capacitor, the pyroelectric device is discharged when connected to a resistor, R_b. Electric current through the resistor and voltage across the resistor represent the heat flow-induced charge. It can be characterized by two pyroelectric coefficients:

 $P_Q[T] = \frac{dP_s}{dT} \begin{array}{l} \text{Pyroelectric} \\ \text{charge coefficient} \end{array}$ $P_V[T] = \frac{dE}{dT} \begin{array}{l} \text{Pyroelectric} \\ \text{voltage coefficient} \end{array}$ $P_s \begin{array}{l} \text{spontaneous polarization} \\ E \begin{array}{l} \text{electric field strength} \\ \text{T temperature in K} \end{array}$



$$C_e = \frac{\Delta Q}{\Delta V} = \mathrm{k}\varepsilon_0 \frac{A}{h}$$

$$\Delta V = P_Q \frac{A}{C_e} \Delta T = P_Q \frac{h}{\mathbf{k}\varepsilon_0} \Delta T$$

Piezoand pyroelectric materials such as lithiumtantalite and the polarized ceramics are typical materials produce the pyroelectric to sensors. During recent years, deposition of pyroelectric а thin films has been intensively employed in the MEMS technologies. Especially effective is use of leadtitanate-oxide (PbTiO₃) that is a ferroelectric ceramic having both а high pyroelectric coefficient and a high Curie temperature of about 490 °C. This material can be easily deposited on the silicon substrates by the so called sol-gel spin casting deposition method.



It is seen that the electric charge reaches its peak value almost instantaneously, and then decays with a thermal time constant τ_{T} . The physical meaning is this: a thermally induced polarization occurs initially in the most outer layer of the crystalline material (just few atomic layers), whose temperature nearly instantaneously raises to its maximum level. This creates the highest thermal gradient across the material thickness. leading to the maximum polarization. Then, heat propagates through the material, being absorbed by its mass in proportion to thermal capacity, C_{T} , while some of the heat is lost to the surroundings through a thermal resistance, R_T . This diminishes the initial gradient that generates the electric charge. The thermal time constant is a product of the sensors' thermal capacity and thermal resistance:

 $\tau_T = C_T R_T = cAhR_T$

The thermal resistance R_T is function of all thermal losses to the surroundings through *convection*, *conduction*, and *thermal radiation*. For the low frequency applications, it is desirable to use sensors with τ_T as large as practical, while for the high speed applications (for instance, to measure laser pulses), a thermal time constant should be dramatically reduced. For that purpose, the pyroelectric material may be laminated with a heat sink: a piece of aluminum or copper.

When a pyroelectric sensor is exposed to a heat source, we consider a thermal capacity of the source being very large (an infinite heat source), and thermal capacity of the sensor small. Therefore, the surface temperature T_b of a target can be considered constant during the measurement, while temperature of the sensor T_s is a function of time. That time function is dependent on properties of the sensing element: its density, specific heat, and thickness. If the input thermal flux has shape of a step function of time and the sensor is freely mounted in air, the output current can be approximated by an exponential function, so that

$$i = i_0 e^{-\frac{t}{\tau_T}}$$

Hall effect

This physical effect was discovered in 1879 in Johns Hopkins University by E. H. Hall. Initially, the effect had a limited, however, a very valuable application as a tool for studying electrical conduction in metals, semiconductors, and other conductive materials. Nowadays, the Hall sensors are widely used for detecting fields. magnetic position, and displacement of objects.

The effect is based on interaction between moving electric carriers and external magnetic field, known as Faraday's law: development of electromotive force as electric charge moves in magnetic field. In metals, these electric carriers (charges) are electrons. When an electron moves through a magnetic field, upon it acts the sideways force:

$$\vec{F} = q\vec{v} \wedge \overline{B}$$



https://www.youtube.com/watch?v=wpAA3geOYil



Hall effect

Many Hall effect sensors are fabricated from silicon and fall into two general categories:

- the basic sensors,
- integrated sensors.

Other materials used for the element fabrication include InSb, InAs, Ge, and GaAs. In the silicon element, an interface electronic circuit are frequently incorporated into the same wafer. This integration is especially important since the Hall effect voltage is quite small. An example of an integration is the three-axis compass AK8975 for smartphones manufactured by AsahiKasei.

In a discrete Hall Effect sensor, a built-in interface circuit may contain a threshold device thus making an integrated sensor a two-state device. That is, it generates "zero" when magnetic field strength is below the threshold, and produces "one" when magnetic field is strong enough to cross the threshold.

Because of a natural piezoresistivity of silicon, all Hall effect sensors are susceptible to mechanical stress effects. Caution should be exercised to minimize application of stress to the leads or the housing. The sensor is also sensitive to temperature variations because temperature influences resistance of the element. If the element is fed by a voltage source, temperature will change the control resistance, and subsequently the control current. Hence, it is preferable to connect the control terminals to a current source rather than to a voltage source.



Seebeck effect



Video Peltier effect



If the entire loop is made of a uniform material, say cooper, then no current will be observed, even if the temperature along the conductor is not uniform. Electric fields in the left and right arms of the loop produce equal currents $i_a=i_b$ which cancel one another, resulting in zero net current.

observe In order to thermoelectricity, it is necessary to have a circuit composed of two different materials and we can then measure the net difference between their thermoelectric properties. In Cu the loop of two dissimilar metals produce net current $\Delta i = i_a - i_b$. The actual current depends on many factors, including the shape and size of the conductors. If, on the other hand, instead of current we measure the net voltage across the broken conductor, the potential will depend only on the materials and the temperature does difference. It not depend on any other factors.

 $V_a - V_b = (\alpha_a - \alpha_b)(T_a - T_b)$

Seebeck effect



Voltage as function of a temperature gradient for a thermocouple with a high degree of accuracy can be approximated by a second-order equation

$$V_{AB} = a_0 + \alpha_1 T + \alpha_2^2 T^2$$

Then a differential Seebeck coefficient for ta thermocouple can be found by differentiating the equation by temperature:

$$\frac{dV_{AB}}{dT} = \alpha_1 + \alpha_2 T$$

It is seen that the coefficient is a linear function of temperature. Sometimes this coefficient α_{AB} is called the sensitivity of a thermocouple junction.

There is a very useful property of a joint: the Seebeck coefficient does not depend on the nature of the junction, metals may be pressed together, welded, fused, soldered, twisted, etc. What counts is temperature of the junction and the actual metals. The Seebeck effect is a direct conversion of thermal energy into electric energy.

Characteristics of thermocouple types

Junction material	Sensitivity (@ 25ºC) [µV/ºC]	Temperature range (°C)	Applications	Designation
Copper/constantan	40.9	-270 to 400	Oxidation, reducing, inert, vacuum. Preferred below 0°C. Moisture resistant.	Т
Iron/constantan	51.7	-210 to +760	Reducing atmosphere.and Avoidoxidation and moisture.	J
Cromel/alumel	40.6	-270 to +1372	Oxidation and inert atmospheres	К
Chromel/constantan	60.9	-270 to 1000		Е
Pt(10%)/Rh-Pt	6.0	-50 to 1768	Oxidation and inert atmospheres, avoid reducing atmosphere and metallic vapors	S
Pt(13%)/Rh-Pt	6.0	-50 to 1768		R
Silver/Paladium	10.0	200 to 600		
Constantan/Tungsten	42.1	0 to 800		
Silicon/Aluminium	446	-40 to 150	Thermopiles and micromachines sensors	
Characteristics of thermocouple types





Jean Charles Athanase Peltier (1785-1845 FR)





The Peltier effect concerns the reversible absorption of heat, which usually takes place when an electric current crosses a junction between two dissimilar metals.

i is the current and *t* is time. The Peltier coefficients Π_i have a dimension of voltage and represents thermoelectric properties of the material. It should be noted that produced and absorbed heat does not depend on temperature at the other sides of the material.

The Peltier effect is used for two purposes: it can produce heat or "produce" cold (remove heat), depending on the direction of electric current through the junction. This makes it quite useful for the devices where precision thermal control is required. Apparently, the Peltier effect is of the same nature as the Seebeck effect. It should be well understood that the Peltier heat is different from that of the Joule. The Peltier heat depends linearly on magnitude of the current flow as contrasted to Joule heat. This effect is a basis for operation of thermoelectric coolers, which are used for cooling of the photon detectors operating in the far-infrared spectral range and the chilled mirror hygrometers.

Alternate physical compression and expansion of medium (solids, liquids, and gases) with certain frequencies are called sound waves. The medium contents oscillate in the direction of wave propagation, hence these waves are called longitudinal mechanical waves. The name sound is associated with the hearing range of a human ear which is approximately from 20 to 20000 Hz. Longitudinal mechanical waves below 20 Hz are called infrasound and above 20000 Hz (20 kHz) ultrasound. If the classification was made by other animals, like dogs, the range of sound waves surely would be wider since dogs can hear up to 45 kHz.

Detection of infrasound is of interest with respect to analysis of building structures, earthquake prediction, and other geometrically large sources. When infrasound is of a relatively strong magnitude it can be if not heard, at least felt by humans, producing quite irritating psychological effects.

Audible waves are produced by vibrating strings (string music instruments), vibrating air columns (wind music instruments), and vibrating plates (some percussion instruments, vocal cords, loudspeakers). Whenever sound is produced, air is alternatively compressed and rarefied. These disturbances propagate outwardly. A spectrum of waves may be quite different: from simple monochromatic sounds from a metronome or an organ pipe, to a reach multiharmonic violin sound. Acoustic noise may have a very broad spectrum. It may be of a uniform distribution of density or it may be *colored* with predominant harmonics at some of its portions.

When a medium is compressed, its volume changes from V to V + Δ V. The ratio of change in pressure, Δ p, to relative change in volume is called the bulk modulus of elasticity of medium:

$$B = -\frac{\Delta p}{\Delta V/V} = \rho_0 v^2$$

 ho_0 is the density outside the compression zone and v is the speed of sound in the medium

$$v = \sqrt{\frac{B}{\rho_0}}$$



Hence, the speed of sound depends on the elastic (B) and inertia (ρ_0) properties of the medium. Since both variables are functions of temperature, the speed of sound also depends on temperature. This feature forms a basis for the acoustic thermometers.

If we consider propagation of a sound wave in an organ tube, each small volume element of air oscillates about its equilibrium position. For a pure harmonic tone, the displacement of a particle from the equilibrium position may be represented by:

$$y = y_m \cos\frac{2}{\lambda}(x - \nu t)$$

 y_m is the displacement from the equilibrium position.

In practice, it is more convenient to deal with pressure variations in sound waves rather than with displacements of the particles. It can be shown that the pressure exerted by the sound wave is:

$$p = k\rho_0 v^2 y_m \sin(kx - \omega t)$$

Therefore, a sound wave may be considered as a pressure wave.

Pressure at any given point in media is not constant and changes continuously, and the difference between the instantaneous and the average pressure is called an acoustic pressure P. During the wave propagation, vibrating particles oscillate near a stationary position with the instantaneous velocity ξ . The ratio of the acoustic pressure and the instantaneous velocity is called an *acoustic impedance*:

$$Z = \frac{P}{\xi}$$

which is a complex quantity that is characterized by an amplitude and a phase. For an idealized media (no loss) the Z is real and is related to the wave velocity as:

$$Z = \rho_0 v$$

We can define intensity I of a sound wave as the power transferred per unit area. Also, it can be expressed through the acoustic impedance:

$$I = P\xi = \frac{P^2}{Z}$$

It is common, however, to specify sound not by intensity but rather by a related parameter β , called the sound level and defined with respect to a reference intensity $I_o = 10^{-12} \text{ W/m}^2$

$$\beta = 10 \log\left(\frac{I}{I_0}\right)$$



The magnitude of I_0 was chosen because it is the lowest ability of a human ear. The unit of β is a decibel (dB), named after Alexander Graham Bell. If If $I=I_0$, $\beta = 0$. Pressure levels also may be expressed in decibels as:

$$\Pi = 20 \log\left(\frac{p}{p_0}\right)$$

where $p_0 = 2 \times 10^{-5} \text{ N/m}$. Since sound is a propagating pressure wave, theoretically it can be measured by pressure sensors adapted for the media where the wave propagates. Sound pressure in several respects differs from other types of pressure (mostly by frequency and intensity ranges), thus a sound (acoustic) sensor should have a special set of characteristics for the efficient conversion of the oscillating pressure into useful electrical signals.

Temperature and Thermal Properties of Materials

Our bodies have a *sense* of temperature, which by no means is an accurate method to measure outside heat. Human senses are not only nonlinear, but also relative with respect to our previous experience. Nevertheless, we can easily tell the difference between warmer and cooler objects. Then, what is going on with these objects that they produce different thermal perceptions?



Every single particle in this Universe exists in perpetual motion. **Temperature of a volume of a material, in the simplest way, can be described as a measure of an average kinetic energy of vibrating particles**. The stronger the particle movement the higher temperature. The average kinetic energy of a very large number of moving particles determines macroscopic temperature of an object.

These processes are studied by thermodynamics and statistical mechanics. Here, however, we are concerned with the methods and devices that are capable of measuring macroscopic average kinetic energy of vibrating particles, which is the other way to say temperature of the object. Since temperature is related to movement of molecules, it is closely associated with **pressure**, which is defined as the force applied by moving molecules per unit area.

When atoms and molecules in a material move, they interact with each other: a jiggling atom agitates a neighbouring atom and transfers to it portion of its kinetic energy, so the neighbour starts vibrating more intensely and kicks and pulls its next neighbours with the increased forces. This agitation propagates through the material, elevating its temperature. Since an atom contains moving electrons swirling around its nucleus like a cloud of the electric current, thermal agitation causes that current to move and thus producing electromagnetic waves.

Temperature and Thermal Properties of Materials

Hence, every vibrating atom acts as a microscopic radio transmitter that emanates electromagnetic radiation to the surrounding space in relation to its own jiggling. These two types of activities form a basis for heat transfer from warmer to cooler objects: conduction and radiation. The stronger the atomic jiggling the hotter the temperature and the stronger the electromagnetic radiation. Special devices (we call them thermometers), which either contact the object or receive its electromagnetic radiation, produce physical responses, or signals. These signals becomes a measure of the object's temperature.

The word thermometer first appeared in literature in 1624 in a book by J. Leurechon, entitled *La Récréation Mathématique*. The author described a glass water-filled thermometer whose scale was divided by 8°. The first pressure- independent thermometer was built in 1654 by Ferdinand II, Grand Duke of Tuscany in form of an alcohol-filled hermetically sealed tube.

Thermal energy is what we call heat. Heat is measured in calories. One calorie (cal) is equal to amount of heat which is required to warm up by 1 °C 1 g of water at normal atmospheric pressure.



Temperature scales

There are several scales to measure temperature. To make a linear scale (for convenience, all thermometers have linear scales), at least two reference points are required. Usually one of these points is called a zero point. A first zero for a scale was established in 1664 by Robert Hooke at a point of freezing distilled water. In 1694 Carlo Renaldi of Padua suggested to take a melting point of ice (zero point) and a boiling point of water (second point) to define a linear span of his thermometer. He divided the span by 12 equal parts. Unfortunately, his suggestion had been forgotten for almost 50 years. In 1701, Newton also suggested for the zero point to use the temperature of melting ice and for the second point he chose the armpit temperature of a "healthy Englishman", he labeled that point *12*. At Newton's scale, water was boiling at point number 34. Daniel Gabriel Fahrenheit, a Dutch instrument maker, in 1706 selected zero for his thermometer at the coldest temperature he could produce by mixing water, ice, and sal-ammoniac or household salt. For the sake of convenience, he established the other point at 96°, which was "found in the blood of a healthy man". On his scale, the melting point of pure water was at 32° and the boiling at 212°.

In 1742, Andreas Celsius, professor of astronomy at the University of Uppsala (Sweden), proposed a scale with zero as the melting point of ice and 100 at boiling point of water.

Nowadays, in science and engineering, Celsius and Kelvin scales are generally employed. The Kelvin scale is arbitrarily based on the so-called triple point of water. There is a fixed temperature at a unique pressure of 4.58 mmHg where water vapor, liquid, and ice can coexist. This unique temperature is 273.16 K (degrees kelvin) which approximately coincides with 0 °C. The Kelvin scale is linear with zero intercept (0 K) at a lowest temperature where kinetic energy of all moving particles is equal to zero. This point cannot be exactly attained in practice and is a strictly theoretical limit. It is called the absolute zero.

Temperature scales

Kelvin and Celsius scales have the same slopes,23 i.e., $1 \degree C = 1 \ K$ and $0 \ K = -273.15 \degree C$. So the Kelvin scale is a shifted Celsius scale:

$$^{\circ}\text{C} = ^{\circ}K - 273.15$$

The boiling point of water is at 100 °C = 373.15 °K. In the past, the Celsius scale sometimes was called "centigrade scale". Now, this term is no longer in use.

A slope of the Fahrenheit scale is steeper, because 1 °C 1/4 1.8 °F. The Celsius and Fahrenheit scales cross at -40 °C and F. The conversion between the two scales is :

$$^{\circ}F = 32 + 1.8^{\circ}C$$

which means that at 0 °C, temperature on the Fahrenheit scale is +32 °F.

Thermal expansion

Essentially, all solids expand in volume with an increase in temperature. This is a result of vibrating atoms and molecules. When the temperature goes up, an average distance between the atoms increases, which leads to an expansion of a whole body. The change in any linear dimension: length, width, or height is called a linear expansion. A length, L_2 , at temperature, T_2 , depends on length, L_1 , at initial temperature T_1 and can be approximated by a linear equation:

$$L_{2} = L_{1} [1 + \alpha (T_{2} - T_{1})]$$
$$\alpha = \frac{\Delta L}{L} \frac{1}{\Delta T}$$
Coefficient of linear expansion

For the so-called isotropic materials, α is the same for any direction. The fractional change in area, A, of an object and its volume, V, with a high degree of accuracy can be respectively represented by:

$$A = 2\alpha A \Delta T \qquad \qquad \Delta V = 3\alpha A V \Delta T$$

Thermal expansion

Thermal expansion is a useful phenomenon that can be employed in many sensors where thermal energy is either measured or used as an excitation signal.



Most of such bimetal plate transducers are made of iron-nickel-chrome alloys. They are useful in a temperature range from -75 C and up to +600 °C. $\alpha_X = 20 \cdot 10^{-6}$, $\alpha_Y = 6 \cdot 10^{-6}$, L = 50 mm, $T_2 - T_1 = 10^{\circ}$ C, h = 0.26 mm

Heat capacity

When an object is warmed up, its temperature increases. By warming we mean transfer of a certain amount of heat (thermal energy) into the object. Heat is stored in the object in form of a kinetic energy of vibration atoms. Since different materials are composed of atoms having different atomic weights, which even may be locked into crystalline structures, the kinetic energy of the atomic vibration also will be different. The amount of heat that an object can store is analogous to the amount of water that a water tank can store. Naturally, it cannot store more than its volume, which is a measure of a tank's capacity. Similarly, every object may be characterized by a heat capacity which depends on both: the material properties of the object and its mass, m:

$$C = mc$$

where c is a constant, which characterizes thermal properties of material. It is called the **specific heat** and is defined as:

$$c = \frac{Q}{m\Delta T}$$

The specific heat describes the material while a thermal capacity describes the object, which is made of that material. Strictly speaking, specific heat is not constant over an entire temperature range of a phase of the material. It often changes dramatically when a phase of the material changes, say from solid to liquid. Microscopically, specific heat reflects structural changes in the material.

Heat capacity



The specific heat of water is almost constant between 0 and 100 °C (liquid phase). Almost, but not exactly: it is higher near freezing, and decreases slightly when the temperature goes to about 35 °C and then slowly rises again from 38 to 100 °C.

Heat transfer

There are two fundamental properties of heat, which should be well recognized:

- Heat is totally not specific, that is, once it is produced, it is impossible to say what origin it has.
- <u>Heat can not be contained</u>, which means that it flows spontaneously from warmer to the cooler part of the system and there is no method known to modern science to stop the heat flow entirely.

Thermal energy may be transferred from one object to another by three ways: conduction, convection, and radiation. While conduction and radiation relate to solids, liquids, and gases, convection can transfer heat by an intermediate fluid (liquid or gas). A measurement of any physical quantity always requires transfer of energy. One of the objects being involved in thermal exchange may be a thermal sensor. Its purpose would be to measure the amount of heat that represents certain information about the object producing that heat. Such information may be the temperature, chemical reaction, position of the object, heat flow, etc.

The thermal source has an infinity heat capacity and high thermal conductivity



When heat moves through the layers, a temperature profile within each material depends on its **thickness** and **thermal conductivity**.