Electrical Tech Note — 560

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Sensor Basics

The purpose of a sensor is to detect the presence of something or to measure some aspect of that quantity such as the temperature of a fluid. The quantity being detected or measured is called the *measurand*. This Tech Note only covers the basics of physical devices that are used to measure or detect a quantity. An exciting area of sensor technology is the bio-sensor where the measurand is detected by some biological organism or biochemical change. A traditional physical sensor may be a part of the bio-sensor system.

A *transducer* is something that will sense a desired quantity and provide an output that is proportional to the measurand. The output of a transducer can be mechanical or it can be electrical. The transducer output can be used to control a process or system or it can be stored to provide a record of the operation of the system or process. The terms sensor and transducer are often used interchangeably. The most convenient output of a sensor is an electrical quantity such as voltage that can easily be quantified, transported, manipulated, and stored. An electrical transducer output can easily be *telemetered* to a more convenient location. Telemetering means measuring at a distance. Transducers can be active or passive. An *active transducer* is one that produces a voltage that is proportional to the measurand and does not require an external voltage source. There are only a limited number of ways a voltage can be produced and those methods are covered in this Tech Note. *Passive transducers* do not produce a voltage. Instead, a passive transducer produces a change in a quantity such as resistance, capacitance, or inductance that is proportional to the measurand. The proportionality of a passive transducer can be linear or it can be nonlinear. Passive transducers perform by changing a circuit parameter, however, what is actually happening is that the measurand is changing one of the parameters that determine the resistance, capacitance, or inductance. The quantities that determine the level of resistance, capacitance, and inductance will be discussed in the section on passive transducers. The parameters that determine the resistance of a conductor are the resistivity of the material (ρ), length of conductor (L) and cross-sectional area of the conductor (A). Transducer *parameters* are chosen. In the case of a resistance strain gage a fine wire is bonded to an object. When the object stretches under strain, the gage wire will stretch thus changing the length and cross-sectional area. In this case the chosen parameters are length and cross-sectional area of the strain gage wire but it is usually change in voltage that is measured.

Electrical Quantities and Relationships: Since the output of most transducers is a voltage and the method of detecting or quantifying a measurand depends upon manipulation of an electrical parameter, it is necessary to understand basic electrical quantities and the principles that govern their actions in circuits.

There are three fundamental quantities that govern action within an electrical circuit and they are voltage, current, and resistance. According to a relationship called Ohm’s law circuit current (measured in Amperes) is directly proportional to the applied voltage (measured in Volts). The proportionality constant is resistance (measured in Ohms) and it’s value can be altered in all sorts of ways. Numerous transducers contain a resistive element that is designed to change in value as the intended measurand changes. What is actually measured, however, is the change in voltage or current as a result of the change in resistance.

According to Ohm's law, the voltage across a circuit element is the result of the current flow through that element times the resistance of the element as shown in Equation 560.1. Simple rearrangement of this equation states that the expected current flow in a circuit is the result of dividing the voltage across a circuit element by the resistance of that element, Equation 560.2. By measuring the voltage across a circuit element and the current through the element the resistance of the element can be calculated, Equation 560.3. *Understanding the Ohm's law relationships is absolutely essential to the understanding of electrical circuits and instrumentation*. The accepted engineering symbols for these quantities are **E** for voltage, **I** for current, and **R** for resistance. When represented as caps steady state is usually implied where the values are not changing with time, and when represented as lower case, one or more of the quantities is changing with time. For electronic and instrumentation circuits voltage and current are frequently at the levels of millivolts (mV) or milliamperes (mA) or even at the level of microvolts (µV) or microamperes (µA).

$$\text{Voltage (E)} = \text{Current (I)} \times \text{Resistance (R)} \qquad \text{Equation 560.1}$$

$$\text{Current (I)} = \frac{\text{Voltage (E)}}{\text{Resistance (R)}} \qquad \text{Equation 560.2}$$

$$\text{Resistance (R)} = \frac{\text{Voltage (E)}}{\text{Current (I)}} \qquad \text{Equation 560.3}$$

There is one other electrical quantity that is important to understand when working with electronics and instrumentation and that is the power being expended by a circuit element as current flows through that element. Or it may be the power that a device is capable of supplying to the circuit. The quantities involved are voltage, current, and resistance, and the power expended is the product of the voltage and current (Equation 560.4). The unit of measure of power is the Watt, although for electronic and instrumentation circuits the level may be milliwatts (mW) or even micorwatts (µW). By substituting Ohm's law into the power equation, power can be determined for a circuit or element in terms of the current level and resistance (Equation 560.5) or in terms of the voltage drop and resistance (Equation 560.6). If the power rating of a circuit or element is known it may be necessary to determine the maximum current flow through that circuit or element and that can be accomplished using Equation 560.7. If voltage drop across a circuit or element is needed, then use Equation 560.8. The Watt is a rate of expending energy at one Joule per second. If the energy expended by a circuit or element is needed, multiply the power in Watts by the time in seconds to get energy in Joules.

$$\text{Power (W)} = \text{Voltage (E)} \times \text{Current (I)} \qquad \text{Equation 560.4}$$

$$P = I^2 \times R \qquad \text{Equation 560.5}$$

$$P = \frac{E^2}{R} \qquad \text{Equation 560.6}$$

$$I = \sqrt{P / R} \qquad \text{Equation 560.7}$$

$$E = \sqrt{P \times R} \qquad \text{Equation 560.8}$$

It is important to recognize that for alternating current circuits, or where circuits involve voltage or current that has a magnitude variability with time, the power formula can begin to get complicated because there may be a significant time shift (phase angel) between the current and voltage that must be taken into consideration. This issue is discussed in Tech Note 222, 512, and 513. When working with conditions where the voltage and current have a magnitude variance over time, the voltage and current may be expressed as a root mean square (rms) value. For the majority of direct current circuits the issue of rms values is not important.

As stated earlier the resistance of a conductor is determined by the resistivity (ρ) of the material, the length (l) of the conductive path and the cross-sectional area (A) of the conductive path. The resistance is the product of the resistivity and length divided by the cross-sectional area (Equation 560.9) A passive transducer often has a resistive element where one or more of these quantities varies in some predictable manner with changes in the measurand. The formula may be linear, but the relationship to the measurand often is not linear.

$$\text{Resistance } (R) = \frac{\text{resistivity } (\rho) \times \text{length } (l)}{\text{cross-sectional area } (A)} \qquad \text{Equation 560.9}$$

Before continuing, it is necessary to explain that the fundamental quantities of electricity are charge (measured in Coulombs), energy (measured in Joules) and time (measured in seconds). Charge is either positive (+) or negative (-) and is the result of the movement of electrons through a material. A material can be electrically neutral as a whole, but the electrons can move to one area of the material leaving a lack of electrons (positively charged atoms) in other parts of the material. The electrons actually move relatively slowly through a material, but because they interact with each other, the actual charge seems to move at nearly the speed of light. It is important to note that when a negative charge moves in one direction there is an equal positive charge moving in the opposite direction. This concept is illustrated in Tech Note 211. Sometimes it is important to define the direction of current flow in a dc circuit. Scientists and engineers define current flow as from the positive (+) terminal of the source to the negative (-) terminal. Technicians are sometimes uncomfortable with this concept and define current flow from negative to positive, the same direction the electrons are actually moving.

Current flow measured in amperes is actually the *rate of flow of charge*. One ampere is one Coulomb of charge flowing past a point in one second (Coulombs per second). Voltage is actually the energy imparted to the charge, and one volt is equal to one Joule of energy per Coulomb of charge (Joules per Coulomb). The chemical activity in a battery, for example, may raise the energy level at one terminal with respect to the other terminal to a level of 9 Joules per Coulomb or 9 Volts. It is important to understand the definitions of voltage and current in order to understand capacitance and inductance of a circuit component.

A *capacitor* consists of two metal plates facing each other with a space between them consisting of an insulating material called a dielectric. The fundamental dielectric material is air or a vacuum which have nearly the same characteristics. Other insulating materials used to build capacitors are rated by a quantity called their *dielectric constant* and it is a value relative to air. For example a certain grade of paper may have a dielectric constant of six. This means it's absolute dielectric constant is six times that of air. The dielectric constant for air or a vacuum is approximately 8.85×10^{-12} Farads/m (Coulombs^2/Joule). A capacitor stores electrical charge. A diagram of a simplified capacitor is shown in Figure 560.1. When the capacitor is connected to a dc voltage supply, current does not flow through the capacitor. Current flows until the dielectric has reached it's capacity to store charge and the voltage across the capacitor plates is equal to the source voltage. The energy is actually stored in the dielectric as an electrostatic field. The amount of energy that can be stored by a capacitor is directly proportional to the dielectric constant of the insulating material between the plates, and the area of the metal plates, and it is inversely proportional to the distance between the plates (Equation 560.10). The unit of *capacitance* is the

Farad which is equal to one Coulomb of charge stored in the dielectric with one volt between the plates. The charge (Q) that can be stored by a capacitor is equal to the capacitance (C) in Farads times the voltage (E) between the plates (Equation 560.11). This means that if it takes 10 volts to put one Coulomb of charge in a capacitor dielectric than the capacitance is 0.1 Farad. Typical capacitors used in instrumentation have values in the range of microfarads (µf) and picofarads (pf or µµf). Plate area (A) and distance between the plates (d) are in meters squared and meters. Capacitance is discussed in detail in Tech note 512.

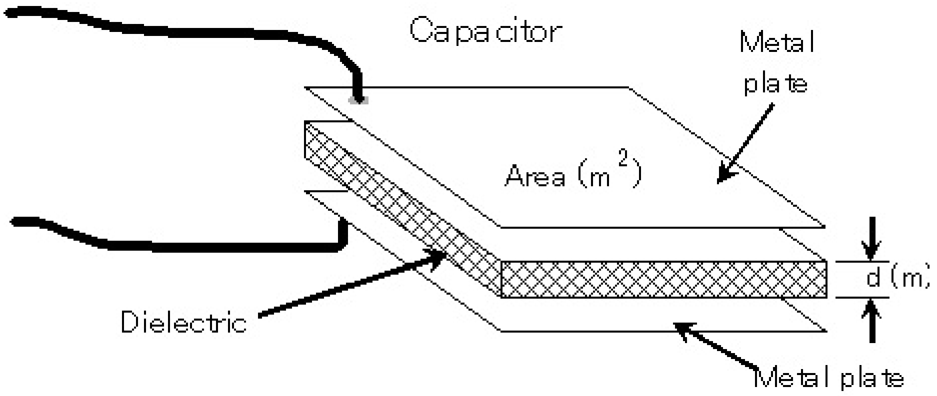

Figure 560.1 *A capacitor consists of two metal plates separated by an insulator called a dielectric. When connected to and electrical source, current flows until the dielectric is fully charged and the voltage between the plates equals the voltage of the source.*

$$\text{Capacitance (C)} = \frac{\text{dielectric constant (K)} \times \text{plate area (A)} \times (8.85 \times 10^{-12})}{\text{distance between plates (d)}} \qquad \text{Equation 560.10}$$

$$\text{Charge (Q)} = \text{Capacitance (C)} \times \text{Voltage (E)} \qquad \text{Equation 560.11}$$

When used in a transducer it is necessary to vary one of the quantities of Equation 560.10 with respect to a change in the measurand. Area can be easily changed by mis-aligning the plates, or the distance between the plates can be changed. The dielectric constant of the insulating material between the plates can be altered by the presence of some substance that enters the dielectric. The change in capacitance then alters the characteristics of an electronic sensing circuit.

The rate at which the charge is put into the capacitor when connected to a voltage source theoretically is instantaneous. There will always be some resistance in series with the capacitor and as a result it will take a time interval for the capacitor to charge and to discharge. The rate at which the voltage builds up on the capacitor plates is the integral of the current divided by the capacitance. As it turns out for practical purposes, the capacitor is considered fully charged in something called five time constants. A time constant is equal to the product of the capacitance and the series resistance. When one time constant has elapsed, the voltage across the capacitor plates has reached 63.2% of it's maximum value. See Tech Note 512 for a detailed discussion of capacitance and the time constant (τ).

The quantity *inductance* involves the effect of a magnetic flux on the current flow in a circuit. When electrical current flows through a wire a magnetic field builds up around the wire with the flux strength directly proportional to the current. Forming a wire into a coil such as shown in Figure 560.2 results in concentration of the magnetic flux produced by each turn of wire in the coil. Coiling a wire in this manner creates what is known as an *inductor*. Another principle involving a magnetic flux and a wire is that if a wire is moved through a magnetic flux such that the wire is moving perpendicular to the direction of the flux, a voltage will be induced into the wire. This induced voltage opposes the current flow that produces the magnetic flux. *Inductance* is the opposition to a change in current, the unit of inductance is the *Henry*, and the symbol for inductance is the letter **L**. More about magnetism and inductance can be found in Tech Notes 217, 317, and 513. An inductor is an electrical component that stores energy in the form of a magnetic flux around the coil of wire. The energy stored in a magnetic flux is proportional to the inductance of the coil times the square of the current. If the current flow is interrupted, the magnetic flux will collapse and the energy stored will be induced into the coil of wire as a voltage that tries to sustain the current flow. The voltage produced is equal to the inductance of the coil (L) times that time rate of change of the current (di/dt). Inductance in Henry (L) is the amount of counter voltage (E_L) produced by the rate of change of current and the fundamental units are Joule Seconds^2 per Coulomb^2.

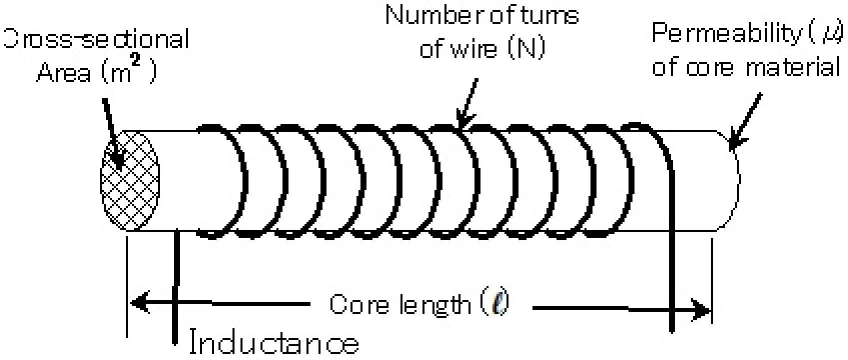

Figure 560.2 *An inductor consists of a coil of wire around a core material where the inductance is the opposition to a change in rate of current flow through the coil. By moving a core with high permeability laterally in and out of the coil the inductance of the coil can be changed significantly.*

Inductance is the opposition to the rate of change of current flow in a conductor. If a coil of wire in energized from a dc source, the inductance of the coil will only be a factor as the current is starting to flow through the coil. Once the current has obtained a steady level, only the resistance of the wire limits the current flow and there is no inductive opposition to the current. A coil has an inductance of one Henry when the coil produces one volt of counter voltage due to the current changing at a rate of one ampere per second. Assume for example that the current in a coil is changing at a rate of 1 ampere in 0.2 seconds. This is a current change of 5 amperes per second. If the coil has an inductance of 1 Henry, the coil will produce one volt of counter voltage for each ampere per second change. In this case the coil will produce 5 volts of counter voltage.

The factors that determine the inductance of a coil are the number of turns of wire in the coil (N), the cross-sectional area of the coil (A), the length of the core (l), and the permeability of the core (μ). Permeability quantifies the quality of a material as a path for a magnetic flux. Air and a vacuum have low permeability while metals containing iron have high permeability. The opposite of permeability is *reluctance*. The inductance of the coil is equal to the core permeability times the square of the number of turns of wire times the cross-sectional area of the core, divided by the length of the core (Equation 560.12). If the fundamental core material is air or a vacuum and the permeability is 1.26×10^{-6} Henry per meter. Other materiels are described by a relative permeability (μ_r) which is compared to the permeability of air. Any material containing iron is a good conductive path for a magnetic flux and has a high relative permeability. The permeability of an iron core can be several thousand compared to air. The way an inductor is used in a sensor is to have some measurand cause a change in the inductance of a coil. The parameter that is easiest to change is the permeability of the core. An iron or steel core can be physically moved into or out-of the coil resulting is significant changes in the inductance of the coil.

$$\textbf{Inductance (L)} = \frac{N^2 \times A \times \mu_r \times (1.26 \times 10^{-6})}{\text{core length (l)}}$$

Equation 560.12

N	number of turns of wire in the coil
A	cross-sectional area of the coil (m^2)
μ_r	relative permeability of core material
1.26×10^{-6}	permeability of air or vacuum (Henry/m)

Another concept important in instrumentation is mutual induction. If a counter voltage can be induced into a coil of wire due to the changing current flow, then a voltage can be induced into a separate wire placed in that same moving magnetic flux. This effect is called mutual induction and it is the principle of operation of the *transformer*. Two separate wires are coiled around the same core in a manner similar to that shown in Figure 560.3. A source where the current is changing (alternating current) is connected to one coil called the primary winding. The moving magnetic flux induces a voltage into the other winding called the secondary. The level of voltage in the secondary winding is proportional to the voltage applied to the primary winding times the ratio of the number of turns on the secondary winding to the primary winding. By placing fewer turns of wire on the secondary winding than the primary winding, the voltage induced into the secondary winding will be lower than the voltage of the primary winding and vice versa. A transformer can be used to change voltage level. Permeability and placement of the transformer core has a significant influence on the process of mutual induction and this principle is used in some sensors. An example is a linear variable differential transformer (LVDT), shown in Figure 560.3, that can be used to detect change in position.

$$\textbf{Secondary Voltage } (E_S) = \textbf{Primary Voltage } (E_P) \times \frac{\text{Secondary turns } (N_S)}{\text{Primary turns } (N_P)}$$

Equation 560.13

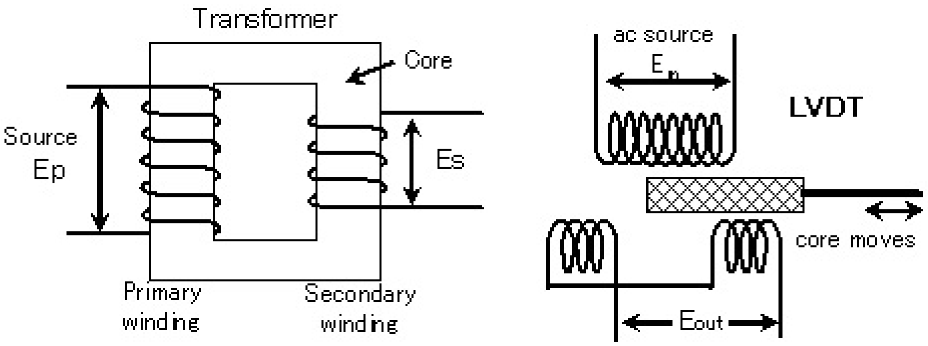

Figure 560.3 *A transformer shown on the left is used to change the voltage and a device such as a linear variable differential transformer can be used to sense change in position.*

Active Transducers: An active transducer is one that can produce a voltage. There are basically six ways that a voltage can be produced. Some of these methods of producing a voltage are directly related to a measurand and are used extensively in sensors.

Chemical activity between two electrodes can produce a voltage. Two dissimilar metals placed in either an acid or alkali solution will result in a voltage produced between the two metal electrodes. Galvanic action, as it is called, is due to the current produced and leads to corrosion.

A voltage produced when a material is exposed to light is called the *photoelectric* effect. There are a number of materials that exhibit this effect. To be most useful as a sensor the voltage produced must be in proportion of the photons of light received at the sensor. Some materials such as a photovoltaic cell made of N-type and P-type silicon wafers simply produce a voltage when exposed to light and may not be well suited as a sensor.

The *thermoelectric* effect is a voltage that is produced when heat is applied to a metal. If a long bar of the same material is heated at one end, a voltage will develop between the two ends. This is called the *Thompson* effect. The most useful effect is where two dissimilar metals are joined together to form a junction. If heat is applied to the junction a voltage will be produced across the two ends of the wire as illustrated in Figure 560.4. This is called the *Seebeck* effect and it has become very useful in measuring temperature. The process works best when the two dissimilar metals are manufactured to have a linear effect with respect to voltage change and two junctions are formed where one junction is placed at a known temperature. This is called a *thermocouple* and one junction is used as the temperature sensor and the other junction is used as the reference. Different materials have been manufactured to provide a linear relationship over specific temperature ranges. Common materials used for thermocouple wire are copper, iron, and special alloys called constantan, chromel, and alumel.

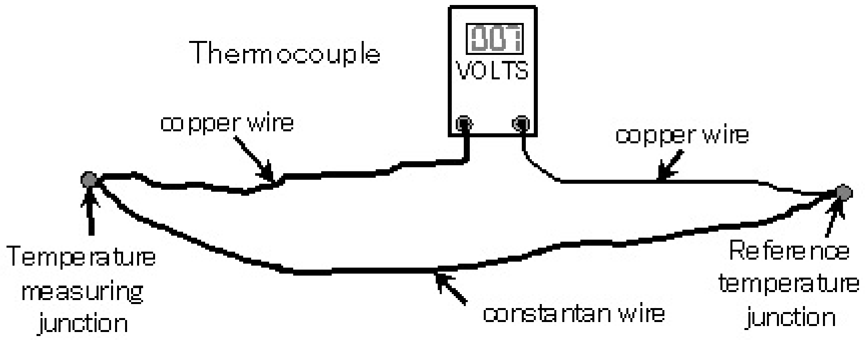

Figure 560.4 *Thermocouples operate on the principle of the Seebeck effect where a voltage is produced when two dissimilar metals are joined in such a manner that two junctions are formed and those junctions are at different temperatures. This is called a thermocouple and the voltage produced is proportional to the difference in temperature between the two junctions.*

The *piezoelectric* effect is when a crystal is placed under pressure a voltage is produced across the crystal. A very weak separation of charge occurs that generally cannot sustain much current flow, but it is a very useful principle used in many transducers where pressure, weight, or acceleration is measured. The piezoelectric effect is best used where the load or pressure is constantly changing such as in a load cell or an accelerometer. Passive resistance strain gages are also common in load cells and accelerometers.

The *electromagnetic* effect was described earlier in this Tech Note when inductance and transformers were discussed. Electromagnetic transducers are very common and they operate on the principle of Faraday's law. If there is motion between a conductor and a magnetic flux, a voltage will be produced in the conductor. Sometimes the magnetic flux is moved across the conductor and sometimes the conductor is energized with alternating current to create a moving magnetic flux.

The final means of producing a voltage is by *electrostatics* or static electricity. By rubbing two types of nonconducting materials together a charge can be built up in the materials. This charge can result in a very high voltage which is often released quickly as an electrical discharge.

Passive Transducers: A passive transducer does not produce a voltage and requires an external voltage source for it's operation. These sensors work by varying an electrical quantity such as resistance, capacitance, or inductance with respect to some measurand. The principles of resistance, capacitance, and inductance were described earlier to provide an understanding of how these quantities can be changed with respect to some measurand. The number of passive transducers is vast and are covered in detail in texts and manufacturers literature.

One type of passive transducer that has not been described earlier in this Tech Note that is often used in transducers is called the *Hall* effect. The sensing element is a flat metal plate. Current is passed through the plate from some source. If the metal plate is placed in a magnetic flux, the charges flowing through the plate will separate such that one side of the plate becomes slightly positively charged and the other side becomes negatively charged. A vary week voltage can be measured across the plate depending upon the density (strength) of the magnetic flux through the plate. The Hall effect is illustrated in Figure 560.5.

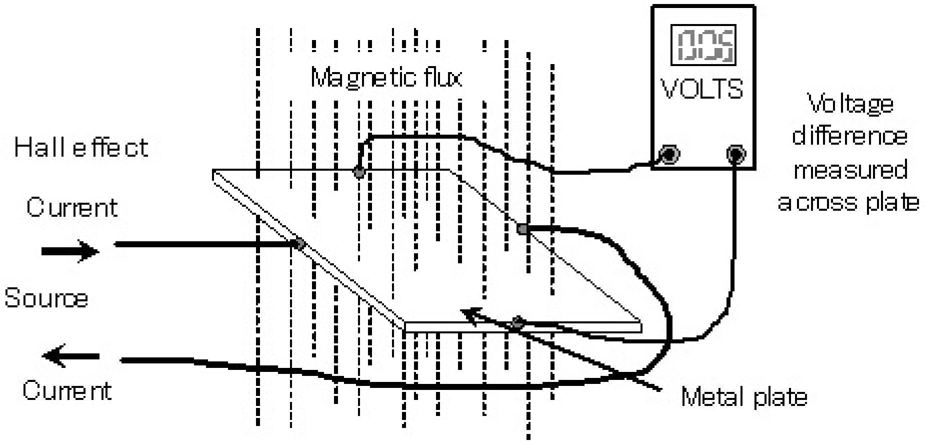

Figure 560.5 *If current is passed through a flat metal plate placed in a magnetic flux, a voltage will develop from one side of the plate to the other in proportion to the density of the magnetic flux. This is called the Hall effect.*