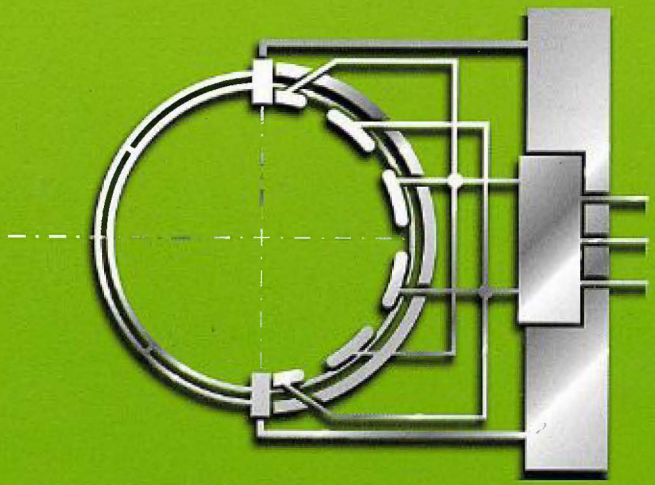
THIRD EDITION

HANDBOOK OF MODERN SENSORS

Physics, Designs, and Applications



JACOB FRADEN

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PHYSICS, DESIGNS, and APPLICATIONS

Third Edition

JACOB FRADEN

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Jacob Fraden
San Diego, California
November 2003

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

$$i = i_0 e^{-t/\tau_T}, \tag{3.83}$$

where i_0 is peak current.

In Fig. 3.29, charge Q and voltage V do not completely return to zero, no matter how much time has elapsed. Thermal energy enters the pyroelectric material from side a (Fig. 3.26), resulting in a material temperature increase. This causes the sensor's response, which decays with a thermal time constant τ_T. However, because the other side, b, of the sensor faces a cooler environment, part of the thermal energy leaves the sensor and is lost to its surroundings. Because sides a and b face objects of different temperatures (one is the temperature of a target and the other is the temperature of the environment), a continuous heat flow exists through the pyroelectric material. The electric current generated by the pyroelectric sensor has the same shape as the thermal current through its material. An accurate measurement can demonstrate that as long as the heat continues to flow, the pyroelectric sensor will generate a constant voltage V_0 whose magnitude is proportional to the heat flow.

3.8 Hall Effect

This physical effect was discovered in 1879 at Johns Hopkins University by E. H. Hall. Initially, the effect had a limited, but very valuable application as a tool for studying electrical conduction in metals, semiconductors, and other conductive materials. Currently, Hall sensors are used to detect magnetic fields and position and displacement of objects [25,26].

The effect is based on the interaction between moving electric carriers and an external magnetic field. In metals, these carriers are electrons. When an electron moves through a magnetic field, a sideways force acts upon it:

$$\mathbf{F} = q v \mathbf{B}, \tag{3.84}$$

where $q = 1.6 \times 10^{-19}$ C is an electronic charge, v is the speed of an electron, and $\mathbf{B}$ is the magnetic field. Vector notations (boldface) are an indication that the force direction and its magnitude depend on the spatial relationship between the magnetic field and the direction of the electron movement. The unit of $\mathbf{B}$ is 1 tesla = 1 newton/(ampere meter) = 10^4 gauss.

Let us assume that the electrons move inside a flat conductive strip which is placed in a magnetic field $\mathbf{B}$ (Fig. 3.30). The strip has two additional contacts at its left and

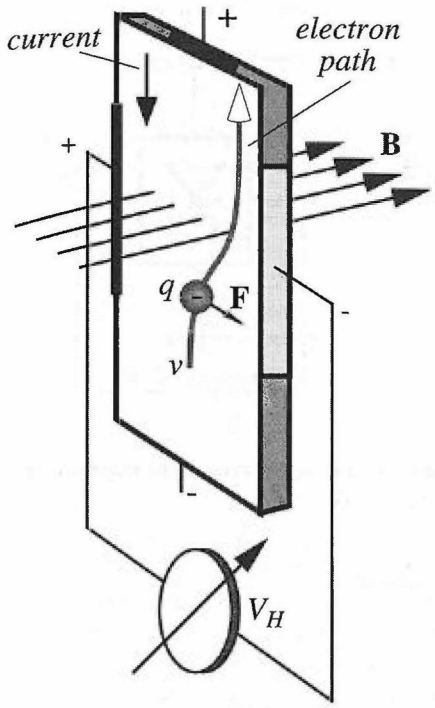


Fig. 3.30. Hall effect sensor. A magnetic field deflects movement of electric charges.

right sides which are connected to a voltmeter. Two other contacts are placed at the upper and lower ends of the strip. These are connected to a source of electric current. Due to the magnetic field, the deflecting force shifts moving electrons toward the right side of the strip, which becomes more negative than the left side; that is, the magnetic field and the electric current produce the so-called *transverse Hall potential difference* V_H. The sign and amplitude of this potential depends on both the magnitude and directions of magnetic field and electric current. At a fixed temperature, it is given by

$$V_H = hiB \sin\alpha, \tag{3.85}$$

where α is the angle between the magnetic field vector and the Hall plate (Fig. 3.31) and h is the coefficient of overall sensitivity whose value depends on the plate material, its geometry (active area), and its temperature.

The overall sensitivity depends on the *Hall coefficient*, which can be defined as the transverse electric potential gradient per unit magnetic field intensity per unit current density. According to the free-electron theory of metals, the Hall coefficient should be given by

$$H = \frac{1}{Ncq}, \tag{3.86}$$

where N is the number of free electrons per unit volume and c is the speed of light.

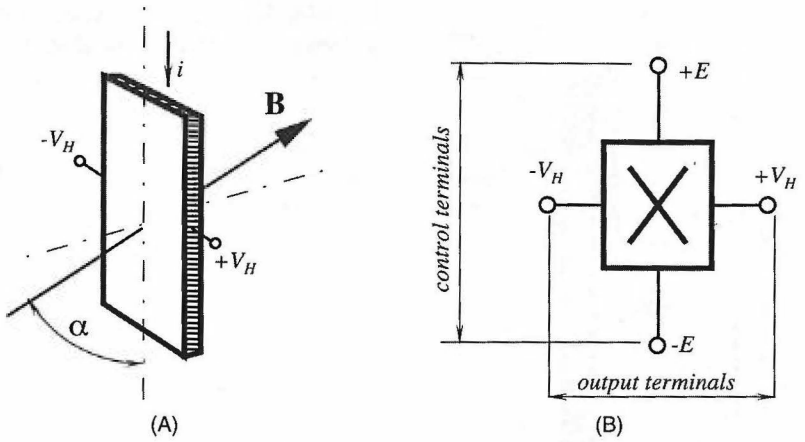


Fig. 3.31. The output signal of a Hall sensor depends on the angle between the magnetic field vector and the plate (A); four terminals of a Hall sensor (B).

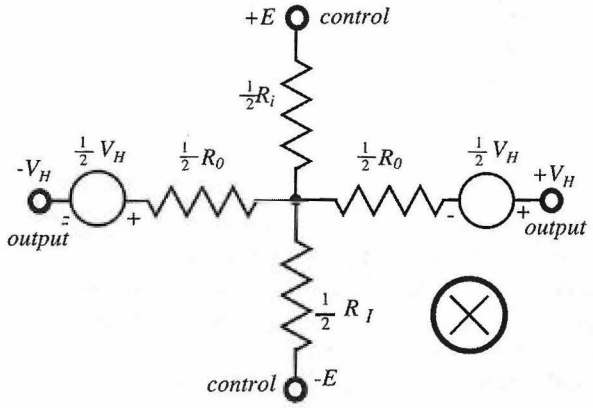
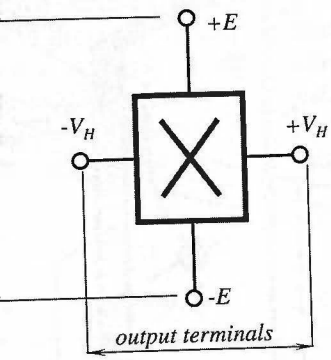


Fig. 3.32. Equivalent circuit of a Hall sensor.

Depending on the material crystalline structure, charges may be either electrons (negative) or holes (positive). As a result, the Hall effect may be either negative or positive.

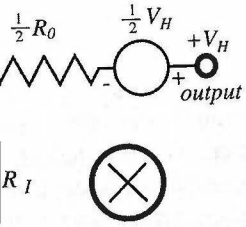
A linear Hall effect sensor is usually packaged in a four-terminal housing. Terminals for applying the control current are called the *control* terminals and the resistance between them is called the *control resistance* R_i. Terminals where the output voltage is observed are called the *differential output terminals* and the resistance between them is called the *differential output resistance*, R_0. The sensor's equivalent circuit (Fig. 3.32) may be represented by cross-connected resistors and two voltage sources connected in series with the output terminals. The cross ⊗ in Figs. 3.31B and 3.32 indicates the direction of the magnetic field from the viewer to the symbol plane.



(B)

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Table 3.2. Typical Characteristics of a Linear Hall Effect Sensor.

Control current	3 mA
Control resistance, R_i	2.2 kΩ
Control resistance versus temperature	+0.8%/°C
Differential output resistance, R_0	4.4 k Ω
Output offset voltage	5.0 mV (at $B = 0$ G)
Sensitivity	60 μV/G
Sensitivity versus temperature	+0.1%/°C
Overall sensitivity	20 V/ΩkG
Maximum magnetic flux density, B	Unlimited

Source: Ref. [27].

The sensor is specified by its resistances, R_i and R_0, across both pairs of terminals, the offset voltage at no magnetic field applied, the sensitivity, and the temperature coefficient of sensitivity. Many Hall effect sensors are fabricated from silicon and fall into two general categories: the basic sensors and the integrated sensors. Other materials used for the element fabrication include InSb, InAs, Ge, and GaAs. In the silicon element, an interface electronic circuit can be incorporated into the same wafer. This integration is especially important because the Hall effect voltage is quite low. For instance, a linear basic silicon sensor UGN-3605K manufactured by Sprague has typical characteristics presented in Table 3.2.

A built-in electronic interface circuit may contain a threshold device, thus making an integrated sensor a two-state device; that is, its output is "zero" when the magnetic field is below the threshold, and it is "one" when the magnetic field is strong enough to cross the threshold.

Because of the piezoresistivity of silicon, all Hall effect sensors are susceptible to mechanical stress effects. Caution should be exercised to minimize the application of stress to the leads or the housing. The sensor is also sensitive to temperature variations because temperature affects the resistance of the element. If the element is fed by a voltage source, the 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.

One way to fabricate the Hall sensor is to use a silicon p-substrate with ion-implanted n-wells (Fig. 3.33A). Electrical contacts provide connections to the power-supply terminals and form the sensor outputs. A Hall element is a simple square with a well with four electrodes attached to the diagonals (Fig. 3.33B). A helpful way of looking at the Hall sensor is to picture it as a resistive bridge as depicted in Fig. 3.33C. This representation makes its practical applications more conventional because the bridge circuits are the most popular networks with well-established methods of design (Section 5.7 of Chapter 5).

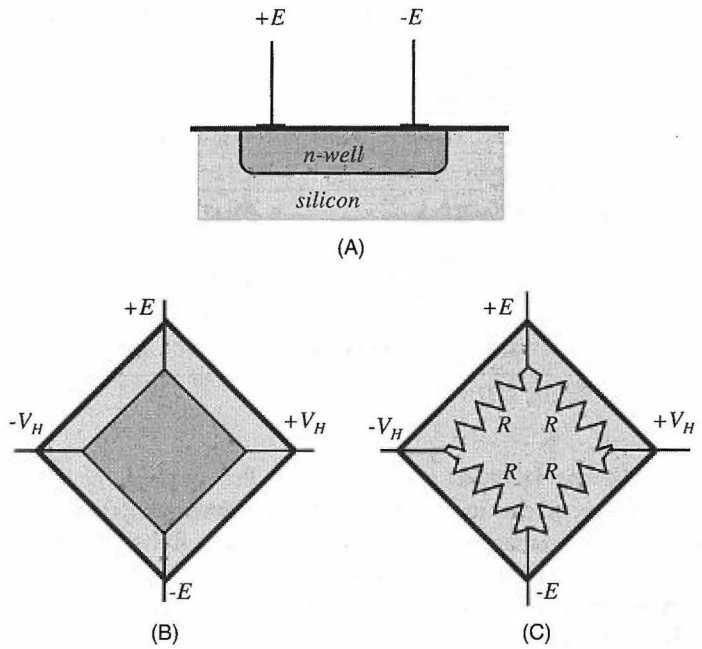


Fig. 3.33. Silicon Hall effect sensor with *n*-well (A and B) and its equivalent resistive bridge circuit (C).

3.9 Seebeck and Peltier Effects

In 1821, Thomas Johann Seebeck (1770–1831), an Estonian-born and Berlin- and Göttingen-educated physician, accidentally joined semicircular pieces of bismuth and copper while studying the thermal effects on galvanic arrangements [28]. A nearby compass indicated a magnetic disturbance (Fig. 3.34A). Seebeck experimented repeatedly with different metal combinations at various temperatures, noting related magnetic field strengths. Curiously, he did not believe that an electric current was flowing and preferred to describe that effect as "thermomagnetism" [29].

If we take a conductor and place one end of it into a cold place and the other end into a warm place, energy will flow from the warm to cold part. The energy takes the form of heat. The intensity of the heat flow is proportional to the thermal conductivity of the conductor. In addition, the thermal gradient sets an electric field inside the conductor (this directly relates to the Thompson effect[10]). The field results

[10] A Thompson effect was discovered by William Thompson around 1850. It consists of absorption or liberation of heat by passing current through a homogeneous conductor which has a temperature gradient across its length. The heat is linearly proportional to current. Heat is absorbed when current and heat flow in opposite directions, and heat is produced when they flow in the same direction.