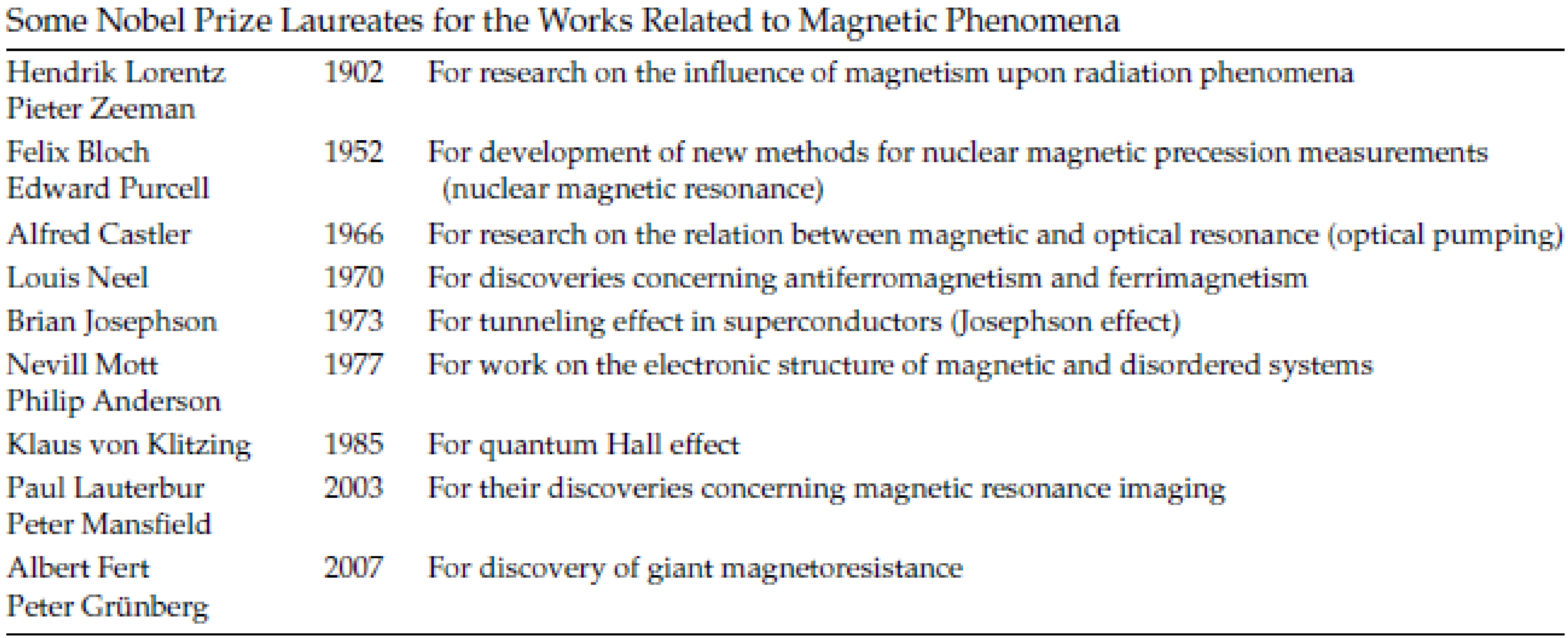
Semiconductor Sensors:

Ch3: Electromagnetic Sensors.

Lecturer: Dr. N. A. Sheini
Shahid Chamran University of Ahvaz

جوایز نوبل برای کشف آثار مغناطیسی:



Some Nobel Prize Laureates for the Works Related to Magnetic Phenomena

Hendrik Lorentz Pieter Zeeman	1902	For research on the influence of magnetism upon radiation phenomena
Felix Bloch Edward Purcell	1952	For development of new methods for nuclear magnetic precession measurements (nuclear magnetic resonance)
Alfred Castler	1966	For research on the relation between magnetic and optical resonance (optical pumping)
Louis Neel	1970	For discoveries concerning antiferromagnetism and ferrimagnetism
Brian Josephson	1973	For tunneling effect in superconductors (Josephson effect)
Nevill Mott Philip Anderson	1977	For work on the electronic structure of magnetic and disordered systems
Klaus von Klitzing	1985	For quantum Hall effect
Paul Lauterbur Peter Mansfield	2003	For their discoveries concerning magnetic resonance imaging
Albert Fert Peter Grünberg	2007	For discovery of giant magnetoresistance

S. Tumanski-Handbook of Magnetic Measurements -CRC (2011)

دو قطبی مغناطیسی:

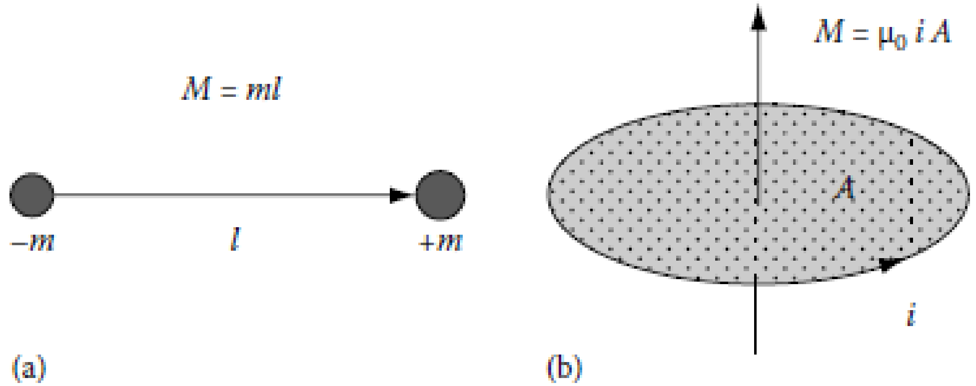
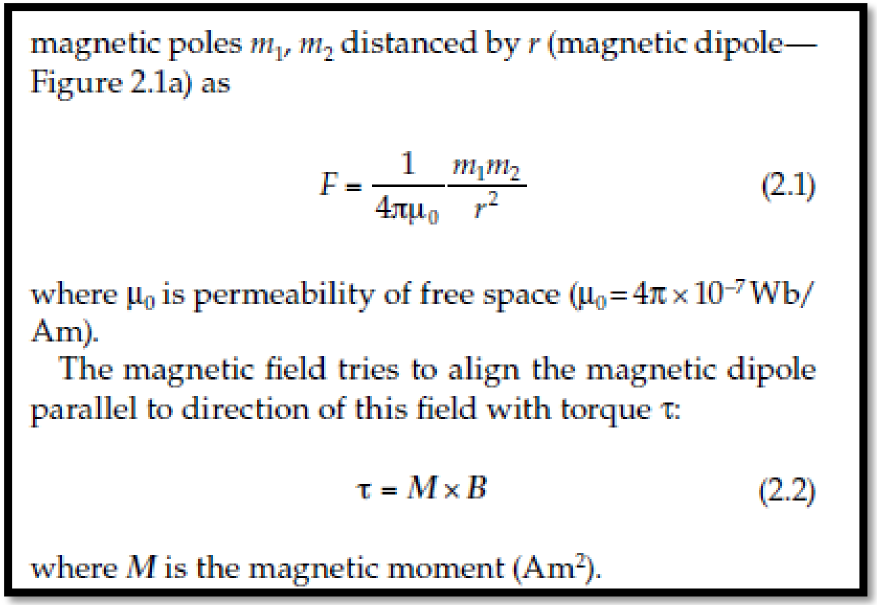


FIGURE 2.1
Two models of elementary entity in magnetism: dipole model proposed by Coulomb (a) and circular loop conducting current proposed by Ampère (b) (*M*, magnetic moment).



magnetic poles m_1, m_2 distanced by r (magnetic dipole—Figure 2.1a) as

$$F = \frac{1}{4\pi\mu_0}\frac{m_1 m_2}{r^2} \tag{2.1}$$

where μ_0 is permeability of free space ($\mu_0 = 4\pi \times 10^{-7}$ Wb/Am).

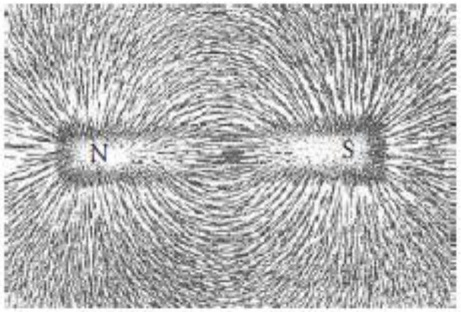
The magnetic field tries to align the magnetic dipole parallel to direction of this field with torque τ:

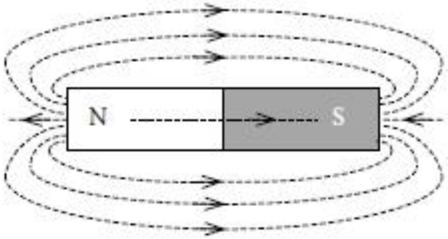
$$\tau = M \times B \tag{2.2}$$

where M is the magnetic moment (Am^2).

S. Tumanski-Handbook of Magnetic Measurements -CRC (2011).pdf

میدان مغناطیسی:





Lorentz showed in 1982 that an EM field acts with a force on a charge q moving with velocity v:

$$F = q(E + v \times \mu_0 H) \qquad (2.9)$$

S. Tumanski-Handbook of Magnetic Measurements -CRC (2011).pdf

واحدهای مغناطیسی:

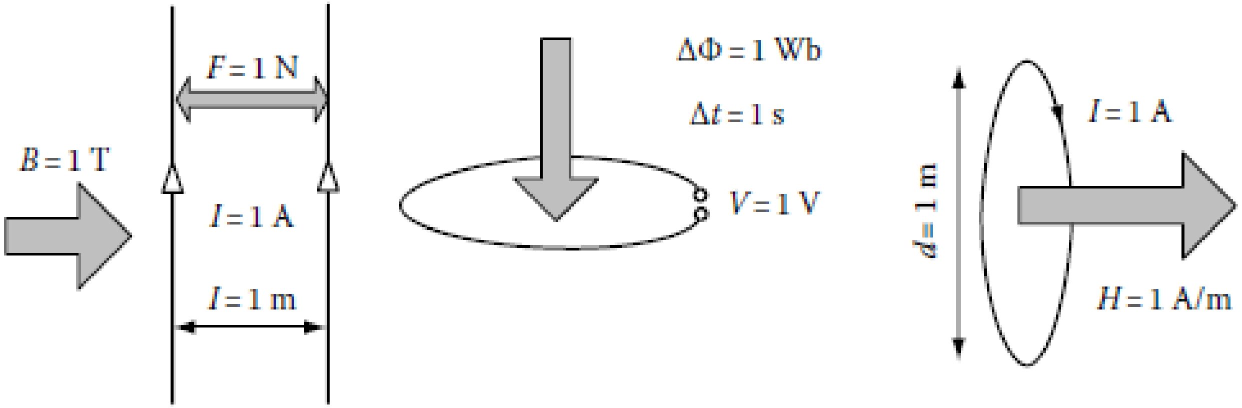
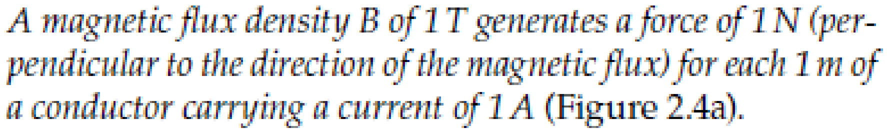
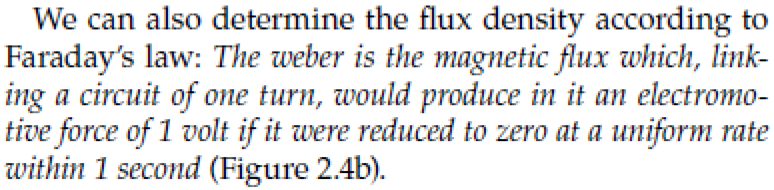


FIGURE 2.4
Various definitions of magnetic field units: tesla (a), weber (b), and A/m (c)



A magnetic flux density B of 1 T generates a force of 1 N (perpendicular to the direction of the magnetic flux) for each 1 m of a conductor carrying a current of 1 A (Figure 2.4a).



We can also determine the flux density according to Faraday's law: *The weber is the magnetic flux which, linking a circuit of one turn, would produce in it an electromotive force of 1 volt if it were reduced to zero at a uniform rate within 1 second* (Figure 2.4b).

S. Tumanski-Handbook of Magnetic Measurements -CRC (2011)

واحدهای مغناطیسی:

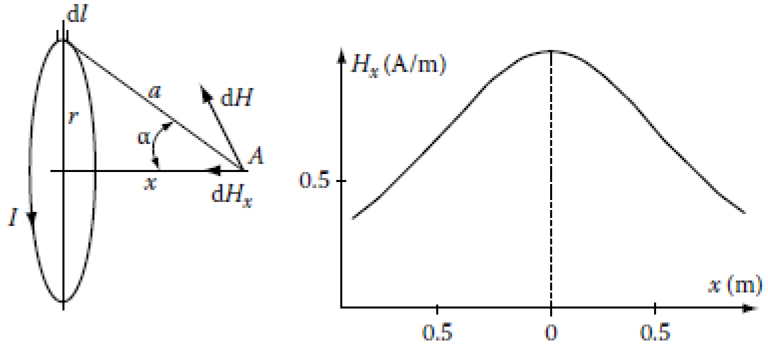


FIGURE 2.2
A circular wire and axial component of magnetic field $H(x)$ generated at the distance x (calculated for $I = 2$ A, $r = 1$ m).

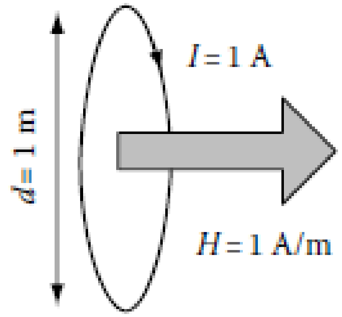
Let us calculate the magnetic field H in the point A (Figure 2.2) generated by the current in a circular wire of radius r. The axial component of this field is

$$dH = \frac{I}{4\pi}\frac{dl}{a^2}\sin\alpha \qquad (2.5)$$

while $a = \sqrt{r^2 + x^2}$ and $\sin\alpha = r/\sqrt{r^2 + x^2}$.

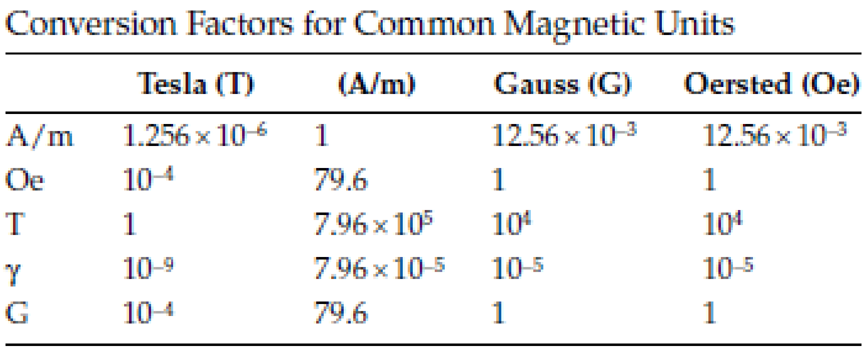
The magnetic field H at the distance x from the axis is

$$H = \oint dH = \frac{I}{2\pi a^2}\sin\alpha \oint dl = \frac{1}{2} I \frac{r^2}{\left(\sqrt{r^2 + x^2}\right)^3} \qquad (2.6)$$



Also the unit of the magnetic field strength can be described according to the Biot–Savart law. We have shown above that a current of 1 A generates in a circle of radius 1 m a magnetic field equal to $I/2r$ (Equation 2.6). So a magnetic field strength of 1 A/m is generated at the center of a single circular turn with a diameter of 1 m of a conductor that carries a current of 1 A.

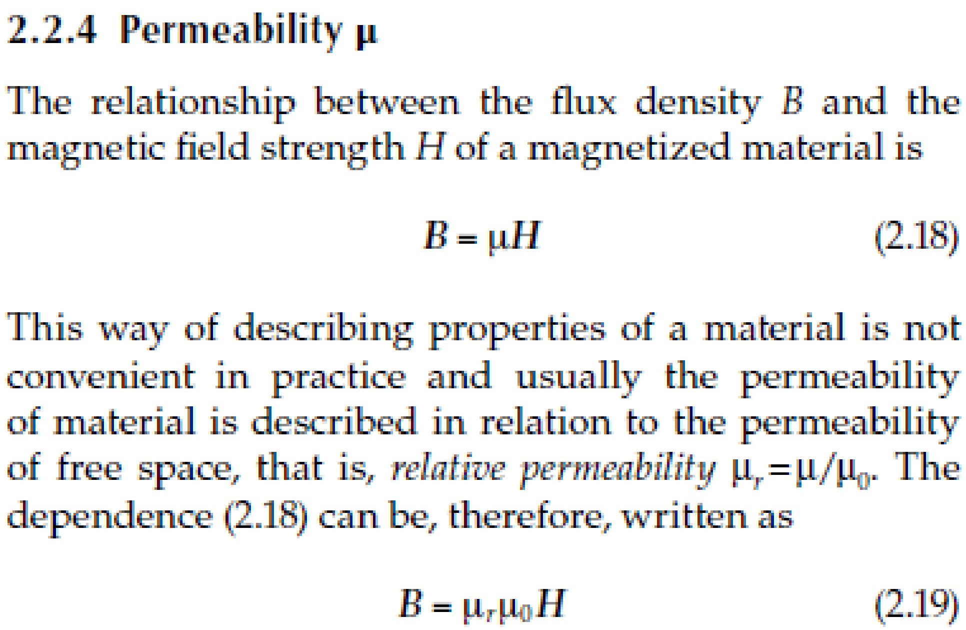
S. Tumanski-Handbook of Magnetic Measurements -CRC (2011)



Conversion Factors for Common Magnetic Units

	Tesla (T)	(A/m)	Gauss (G)	Oersted (Oe)
A/m	1.256×10^{-6}	1	12.56×10^{-3}	12.56×10^{-3}
Oe	10^{-4}	79.6	1	1
T	1	7.96×10^{5}	10^{4}	10^{4}
γ	10^{-9}	7.96×10^{-5}	10^{-5}	10^{-5}
G	10^{-4}	79.6	1	1

گذردهی مغناطیسی:



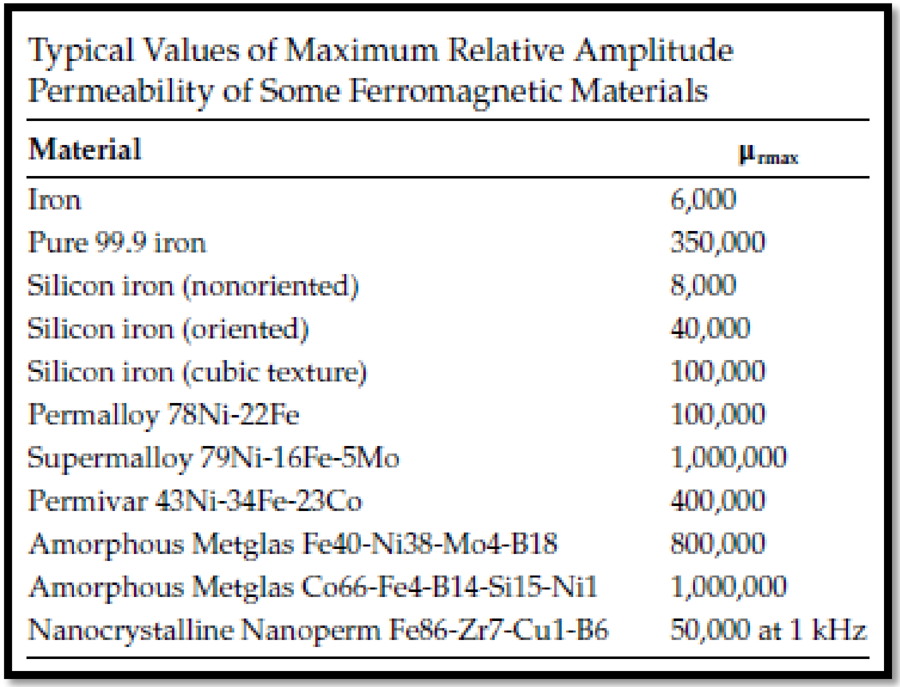
2.2.4 Permeability μ

The relationship between the flux density B and the magnetic field strength H of a magnetized material is

$$B = \mu H \tag{2.18}$$

This way of describing properties of a material is not convenient in practice and usually the permeability of material is described in relation to the permeability of free space, that is, *relative permeability* $\mu_r = \mu/\mu_0$. The dependence (2.18) can be, therefore, written as

$$B = \mu_r \mu_0 H \tag{2.19}$$

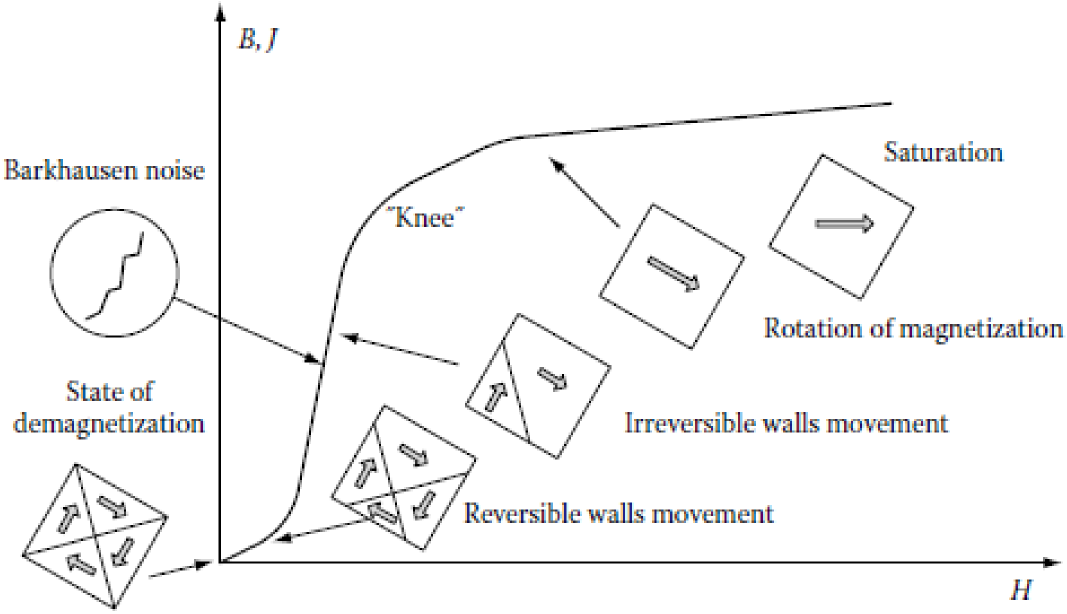


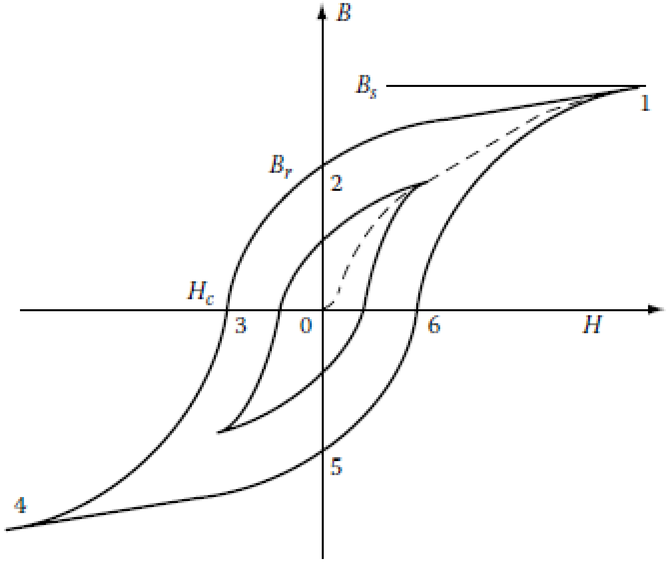
Typical Values of Maximum Relative Amplitude Permeability of Some Ferromagnetic Materials

Material	μ_{rmax}
Iron	6,000
Pure 99.9 iron	350,000
Silicon iron (nonoriented)	8,000
Silicon iron (oriented)	40,000
Silicon iron (cubic texture)	100,000
Permalloy 78Ni-22Fe	100,000
Supermalloy 79Ni-16Fe-5Mo	1,000,000
Permivar 43Ni-34Fe-23Co	400,000
Amorphous Metglas Fe40-Ni38-Mo4-B18	800,000
Amorphous Metglas Co66-Fe4-B14-Si15-Ni1	1,000,000
Nanocrystalline Nanoperm Fe86-Zr7-Cu1-B6	50,000 at 1 kHz

S. Tumanski-Handbook of Magnetic Measurements -CRC (2011)

منحنی مغناطیس شوندگی:



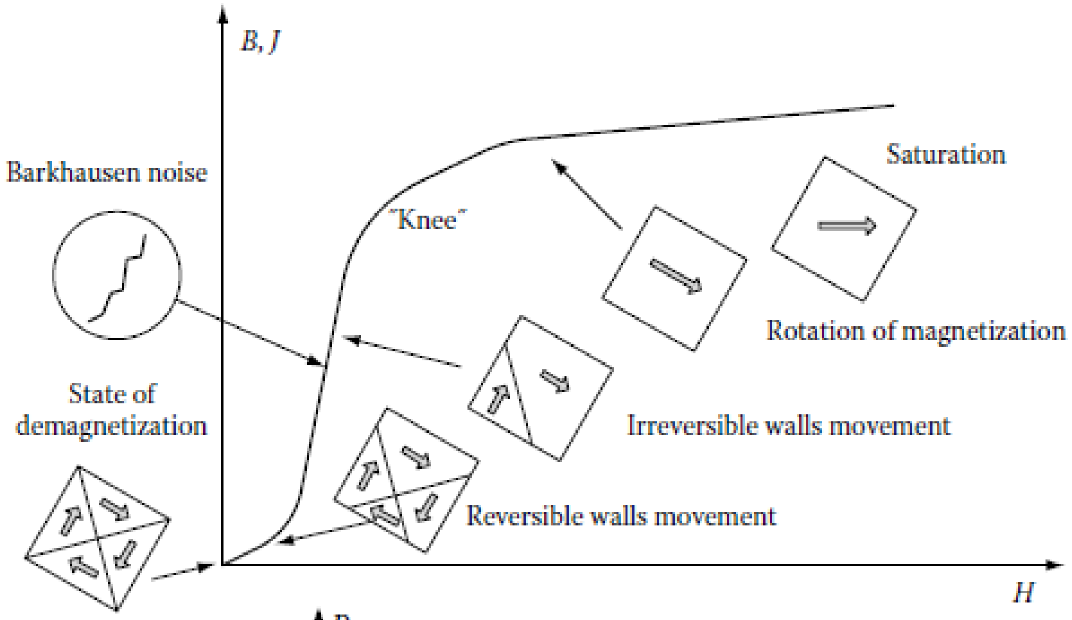


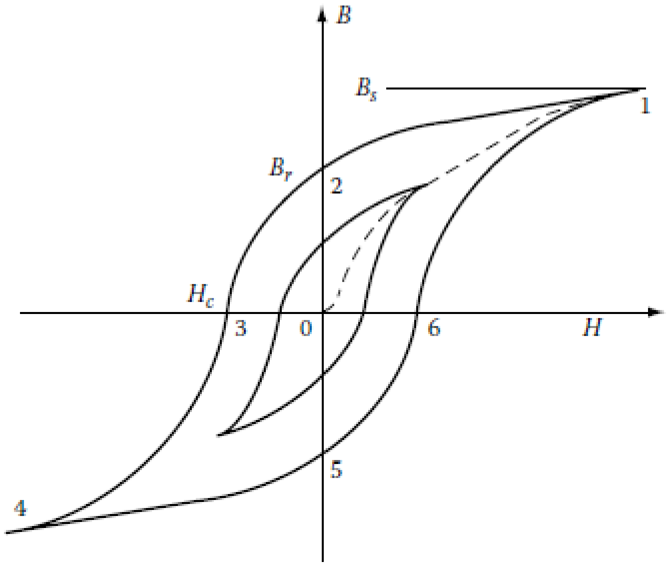
Main Parameters of Hysteresis Loop of Various Soft Magnetic Material

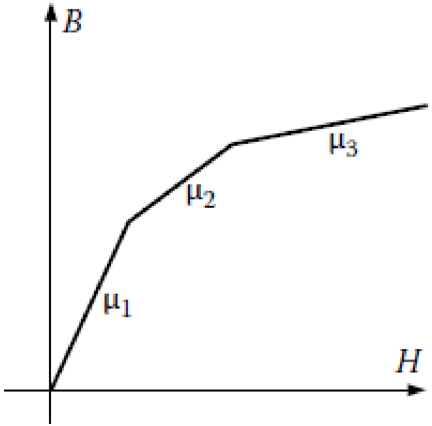
Material	H_c (A/m)	B_s (T)
Iron	70	2.16
Pure 99.9 iron	0.8	2.16
Silicon-iron (nonoriented)	40	1.95
Silicon-iron (oriented)	12	2.01

S. Tumanski-Handbook of Magnetic Measurements -CRC (2011)

منحنی مغناطیس شوندگی:





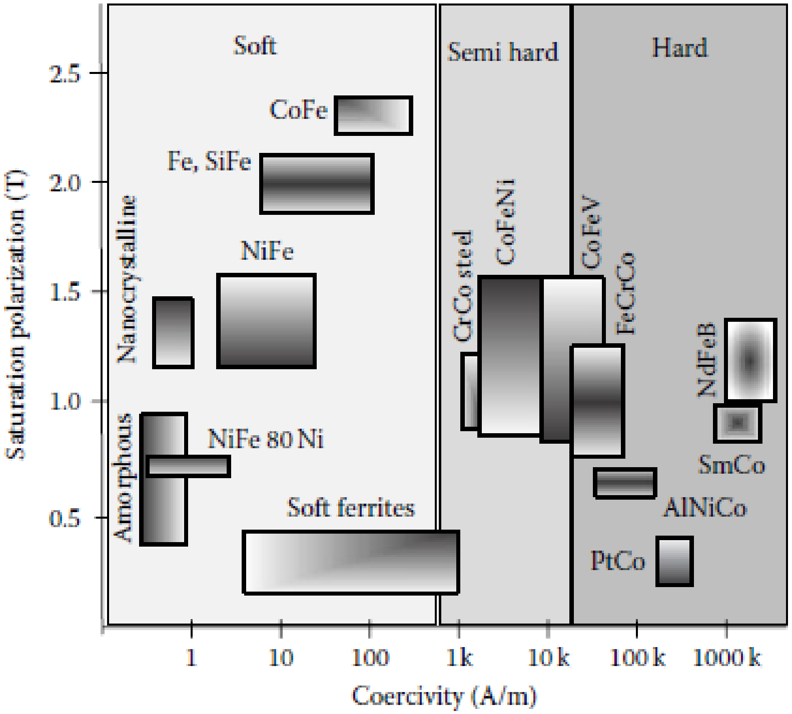


Main Parameters of Hysteresis Loop of Various Soft Magnetic Material

Material	H_c (A/m)	B_s (T)
Iron	70	2.16
Pure 99.9 iron	0.8	2.16
Silicon-iron (nonoriented)	40	1.95
Silicon-iron (oriented)	12	2.01

S. Tumanski-Handbook of Magnetic Measurements -CRC (2011)

مواد مغناطیسی :



S. Tumanski-Handbook of Magnetic Measurements -CRC (2011)

انواع حسگرهای مغناطیسی:

- اثر هال (Hall-Effect Sensors)
- حسگرهای القایی (Induction Sensors)
- شار گیت (Fluxgate Sensor)
- مقاومت مغناطیسی و امپدانس مغناطیسی

  (Magnetoresistive and Magnetoimpedance Sensors)
- حسگرهای **SQUID** (SQUID Sensors)
- حسگرهای رزونانسی و مگنومتر

  (Resonance Sensors and Magnetometers)
- انواع دیگر

  Magnetoelastic and Wiegand-Effect Sensors

S. Tumanski-Handbook of Magnetic Measurements -CRC (2011)

انواع حسگرهای مغناطیسی:

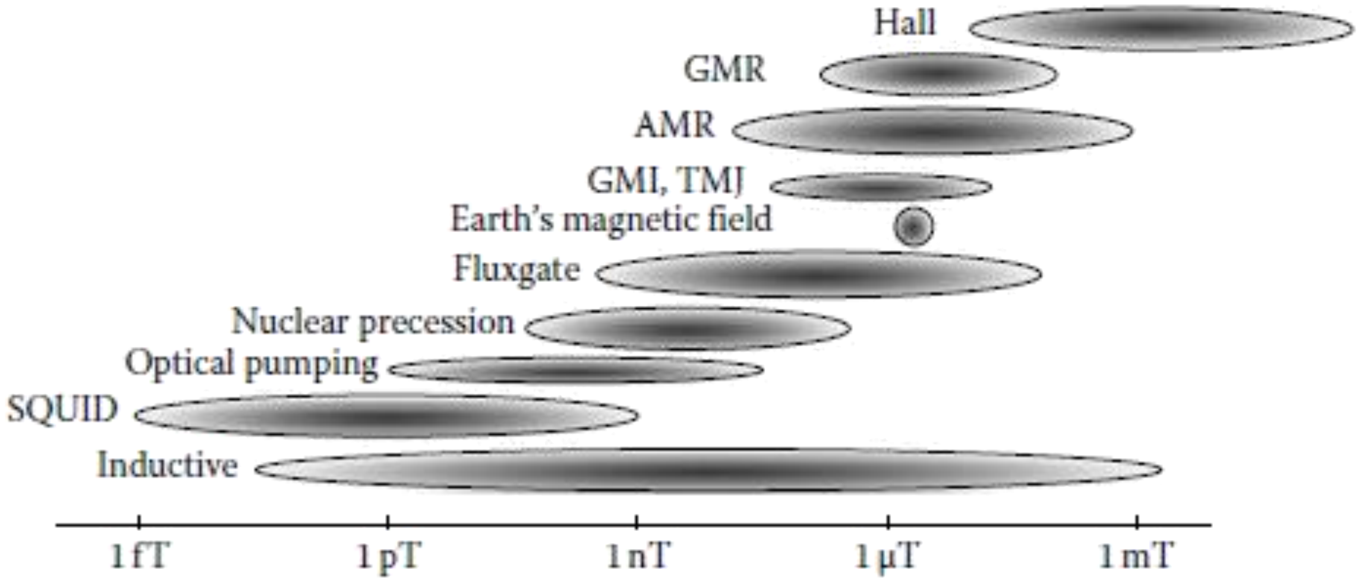
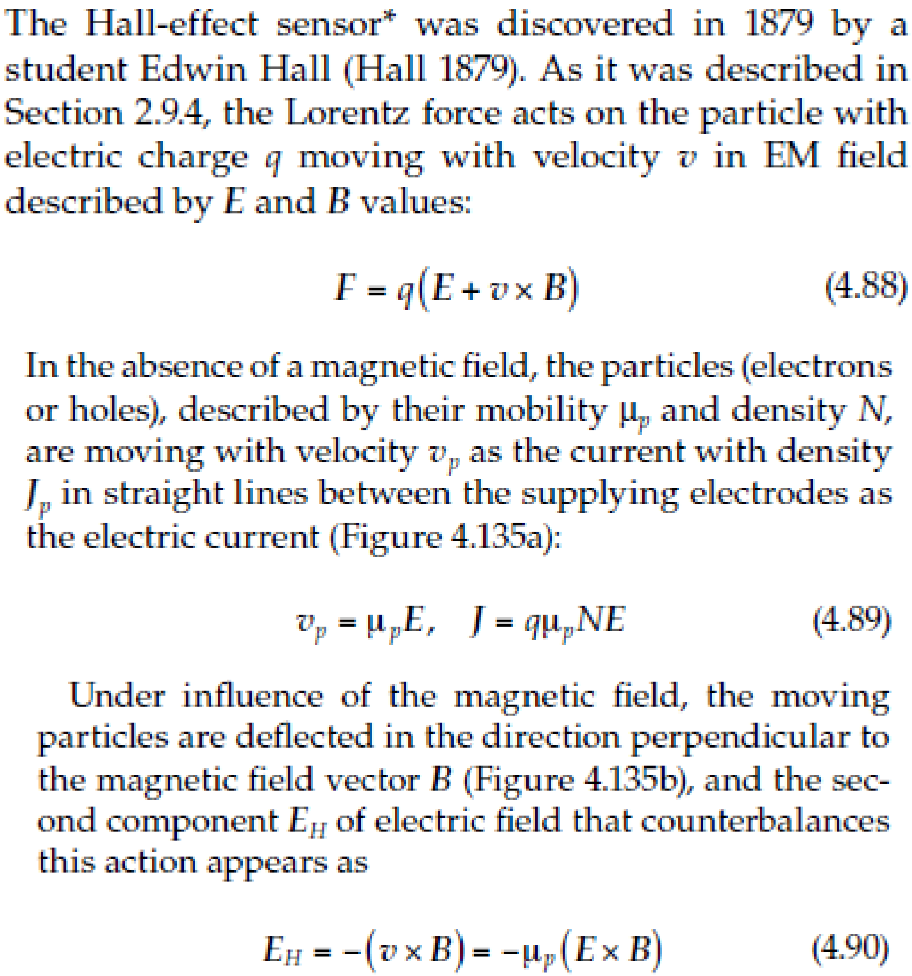


FIGURE 4.1
The range of application of the main magnetic field sensors.

S. Tumanski-Handbook of Magnetic Measurements -CRC (2011)

حسگر هال:



The Hall-effect sensor* was discovered in 1879 by a student Edwin Hall (Hall 1879). As it was described in Section 2.9.4, the Lorentz force acts on the particle with electric charge q moving with velocity v in EM field described by E and B values:

$$F = q\left(E + v \times B\right) \tag{4.88}$$

In the absence of a magnetic field, the particles (electrons or holes), described by their mobility μ_p and density N, are moving with velocity v_p as the current with density J_p in straight lines between the supplying electrodes as the electric current (Figure 4.135a):

$$v_p = \mu_p E, \quad J = q\mu_p NE \tag{4.89}$$

Under influence of the magnetic field, the moving particles are deflected in the direction perpendicular to the magnetic field vector B (Figure 4.135b), and the second component E_H of electric field that counterbalances this action appears as

$$E_H = -\left(v \times B\right) = -\mu_p\left(E \times B\right) \tag{4.90}$$

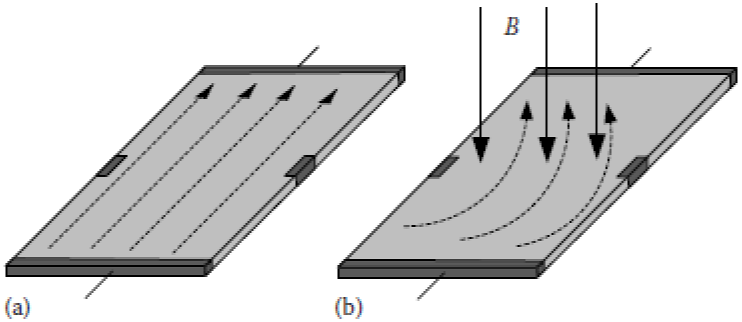


FIGURE 4.135
Current lines without (a) and with magnetic field (b).

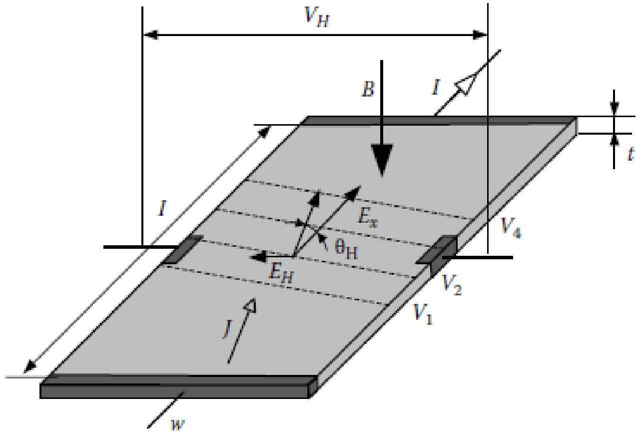


FIGURE 4.136
The Hall sensor (V_1, V_2, V_4—the equipotential lines).

S. Tumanski-Handbook of Magnetic Measurements -CRC (2011)- page 213.

حسگر هال:

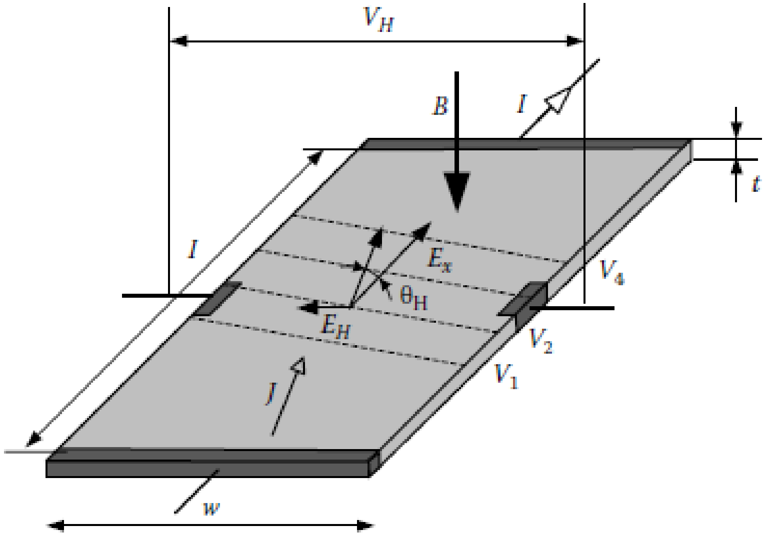


FIGURE 4.136
The Hall sensor (V_1, V_2, V_4—the equipotential lines).

The direction of the current is deflected by the angle θ_H known as the Hall angle (Figure 4.136):

$$\tan\theta_H = \frac{|E_H|}{|E|} \tag{4.91}$$

Taking into account the expression (4.90), we can describe the Hall electric field as

$$E_H = -\frac{1}{qN}(J \times B) = -R_H(J \times B) \tag{4.92}$$

where R_H is the Hall coefficient.

Usually, voltage between the sensing electrodes of the plate of width w is used as the output signal of the Hall sensor:

$$V_H = \mu_p w E_x B_y = R_H w J B \tag{4.93}$$

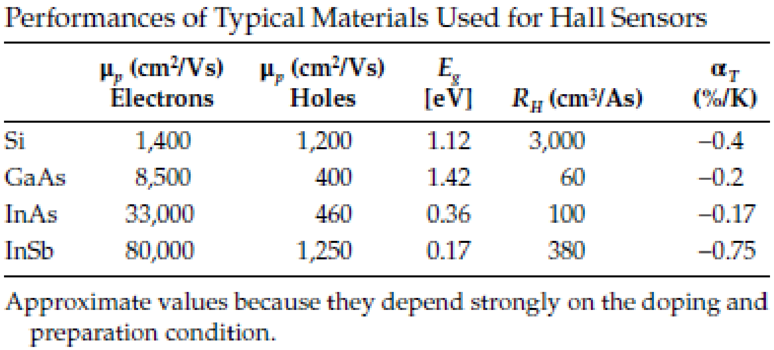
By substituting the current density J in the plate of the thickness t by I/wt, we obtain the most commonly used relation describing the Hall sensor:

$$V_H = \frac{R_H}{t} I \cdot B \tag{4.94}$$

$$V_H = \mu_H \frac{w}{l} V B \tag{4.95}$$

S. Tumanski-Handbook of Magnetic Measurements -CRC (2011)- page 213.

ضریب هال:



Performances of Typical Materials Used for Hall Sensors

	μ_p (cm²/Vs) Electrons	μ_p (cm²/Vs) Holes	E_g [eV]	R_H (cm³/As)	α_T (%/K)
Si	1,400	1,200	1.12	3,000	–0.4
GaAs	8,500	400	1.42	60	–0.2
InAs	33,000	460	0.36	100	–0.17
InSb	80,000	1,250	0.17	380	–0.75

Approximate values because they depend strongly on the doping and preparation condition.

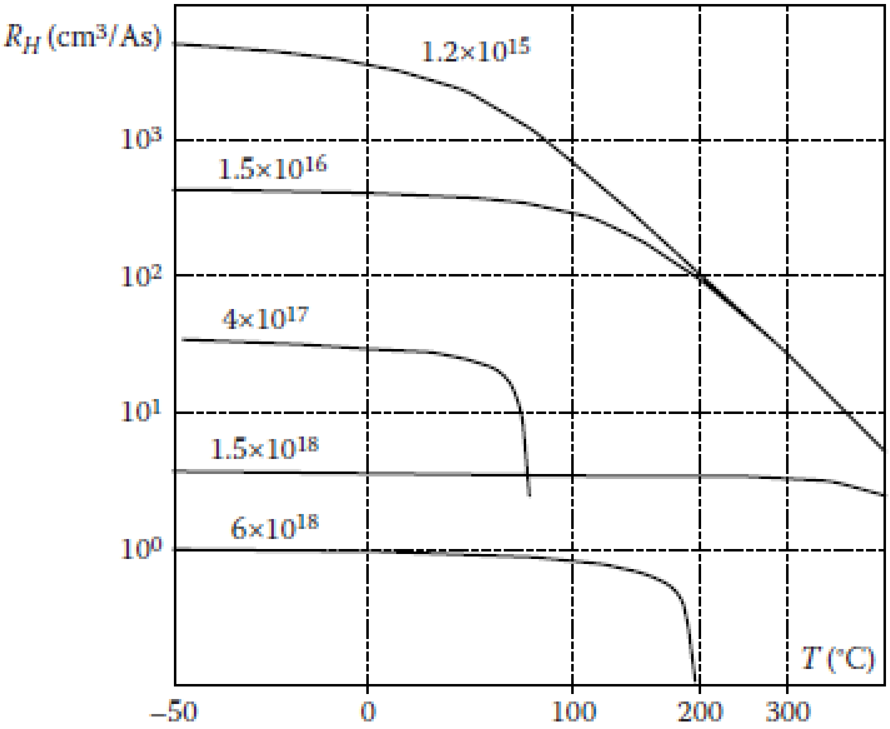


FIGURE 4.137
The Hall coefficient of InAs for various doping densities (indicated electron concentration in cm^{-3}). (After Popovic, R.S., *Hall Effect Devices*, IOP Publishing, Boston, MA, 2004; Folberth, O.G. et al., *Z. Naturforsch.*, 9a, 954.)

S. Tumanski-Handbook of Magnetic Measurements -CRC (2011).

طراحی حسگر هال:

$$V_H = G\frac{R_H}{t} I \cdot B \qquad (4.97)$$

The geometrical factor G is between 0.7 and 0.9. Figure 4.139 presents various shapes of the Hall plates.

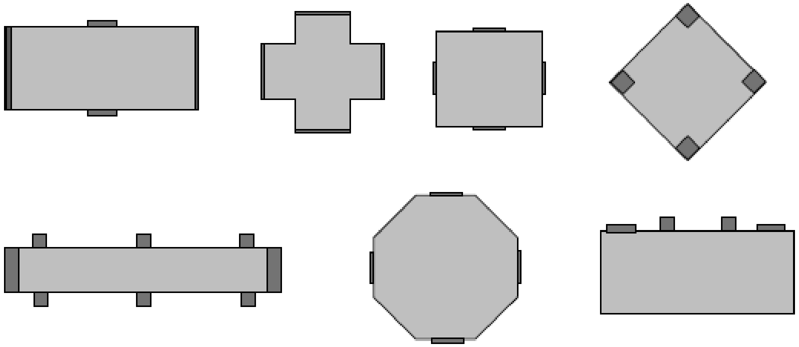


FIGURE 4.139
Various shapes of the Hall plates.

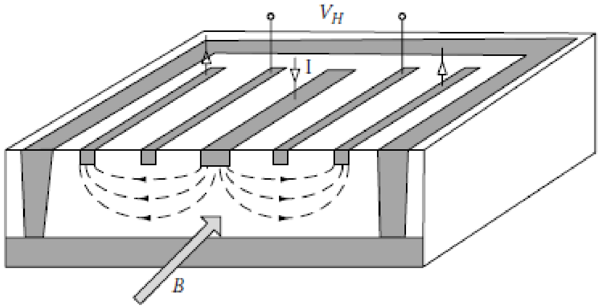


FIGURE 4.141
Design of vertical Hall sensor.

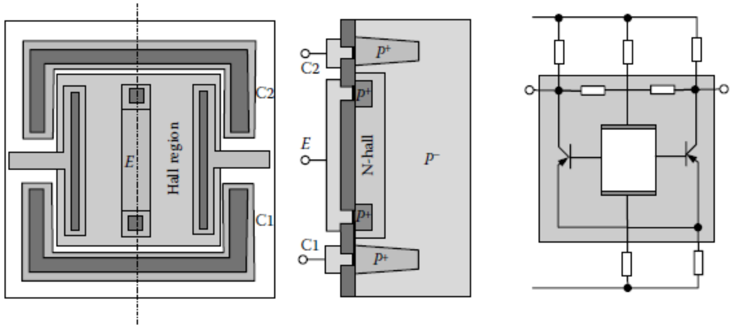
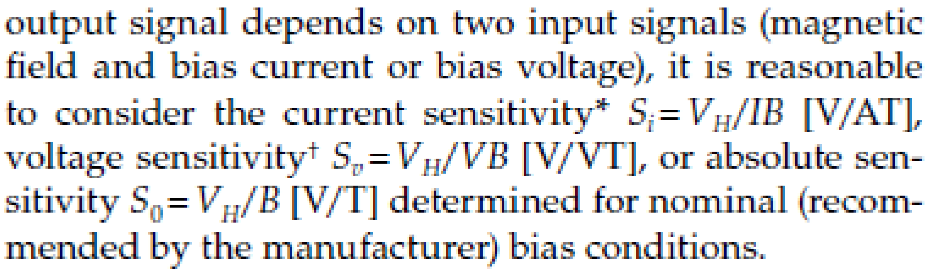


FIGURE 4.140
An example of the Hall sensor with two transistors as the part of differential amplifier. (From Huang, R.M. et al., *IEEE Trans., Electron. Dev.*, 31, 1001, 1984.)

S. Tumanski-Handbook of Magnetic Measurements –CRC (2011).

حساسیت در حسگر هال:

- حساسیت جریانی
- حساسیت ولتاژی



output signal depends on two input signals (magnetic field and bias current or bias voltage), it is reasonable to consider the current sensitivity* $S_i = V_H/IB$ [V/AT], voltage sensitivity† $S_v = V_H/VB$ [V/VT], or absolute sensitivity $S_0 = V_H/B$ [V/T] determined for nominal (recommended by the manufacturer) bias conditions.

$$V_H = \frac{R_H}{t} I \cdot B \qquad (4.94)$$

$$V_H = \mu_H \frac{w}{l} VB \qquad (4.95)$$

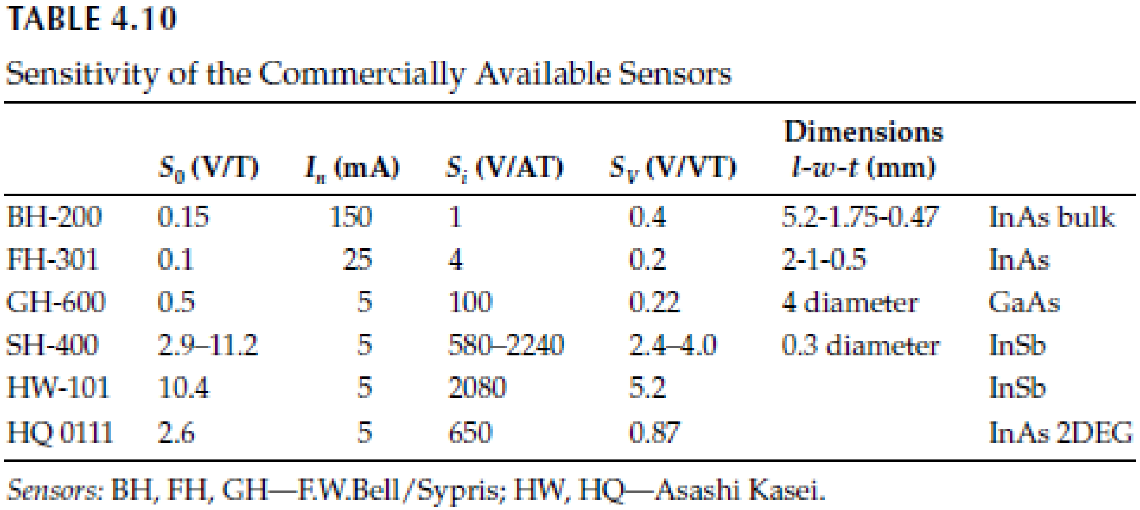


TABLE 4.10

Sensitivity of the Commercially Available Sensors

	S_0 (V/T)	I_n (mA)	S_i (V/AT)	S_v (V/VT)	Dimensions *l-w-t* (mm)	
BH-200	0.15	150	1	0.4	5.2-1.75-0.47	InAs bulk
FH-301	0.1	25	4	0.2	2-1-0.5	InAs
GH-600	0.5	5	100	0.22	4 diameter	GaAs
SH-400	2.9–11.2	5	580–2240	2.4–4.0	0.3 diameter	InSb
HW-101	10.4	5	2080	5.2		InSb
HQ 0111	2.6	5	650	0.87		InAs 2DEG

Sensors: BH, FH, GH—F.W.Bell/Sypris; HW, HQ—Asashi Kasei.

S. Tumanski-Handbook of Magnetic Measurements -CRC (2011)- page 217..

خطا در حسگر هال:

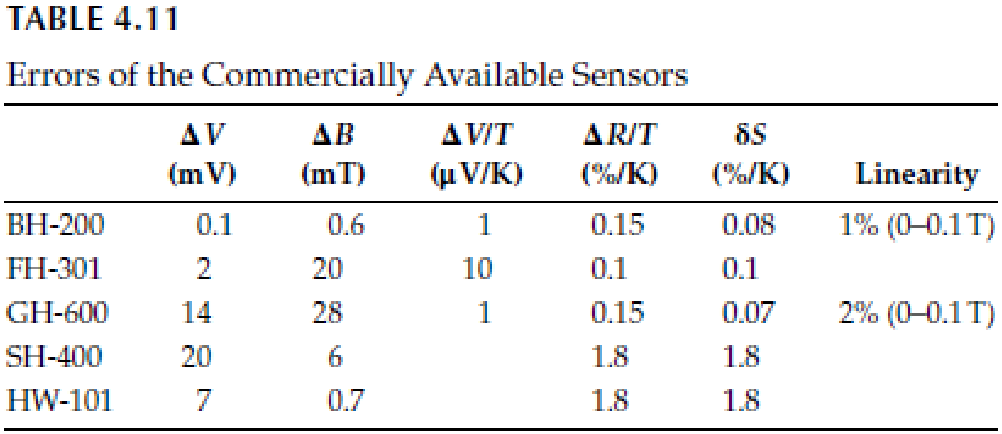


TABLE 4.11

Errors of the Commercially Available Sensors

	Δ*V* **(mV)**	**Δ*B*** **(mT)**	**Δ*V*/*T*** **(μV/K)**	**Δ*R*/*T*** **(%/K)**	**δ*S*** **(%/K)**	**Linearity**
BH-200	0.1	0.6	1	0.15	0.08	1% (0–0.1 T)
FH-301	2	20	10	0.1	0.1	
GH-600	14	28	1	0.15	0.07	2% (0–0.1 T)
SH-400	20	6		1.8	1.8	
HW-101	7	0.7		1.8	1.8	

S. Tumanski-Handbook of Magnetic Measurements -CRC (2011)- page 217.

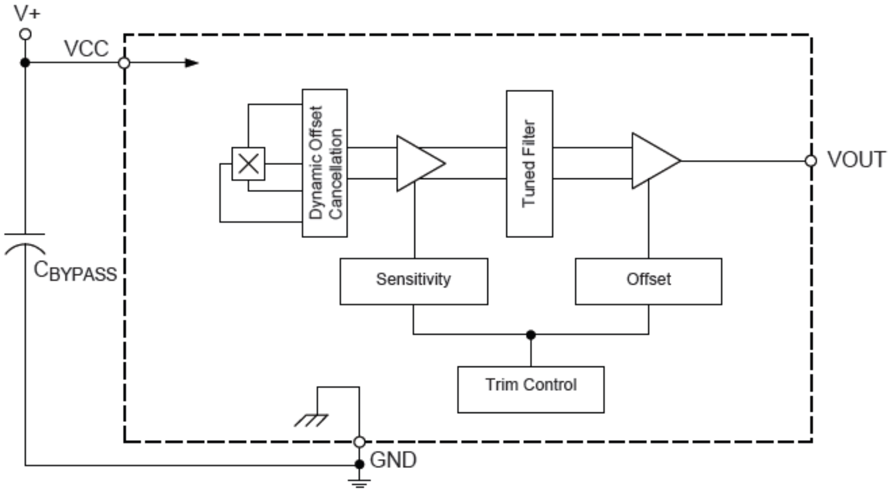
Allegro MicroSystems, LLC

A1304

Linear Hall-Effect Sensor IC with Analog Output, Available in a Miniature, Low Profile Surface Mount Package

FEATURES AND BENEFITS

- 3.3 V supply operation
- Allegro factory programmed offset and sensitivity
- Miniature package
- High bandwidth, low noise analog output
- High speed chopping scheme minimizes QVO drift across operating temperature range
- Temperature-stable quiescent voltage output and sensitivity
- Precise recoverability after temperature cycling
- Wide ambient temperature range: –40°C to 85°C
- Immune to mechanical stress



Functional Block Diagram

Magnetic Characteristics							
Sensitivity[4]	Sens	A1304ELHLX-T	$T_A = 25°C$	3.76	4.0	4.24	mV/G
		A1304ELHLX-05-T		0.2	0.5	0.8	
Sensitivity Temperature Coefficient[3]	TC_{Sens}	$T_A = 85°C$, relative to Sens at 25°C		0.04	0.12	0.2	%/°C
Quiescent Voltage Output (QVO)	$V_{OUT(Q)}$	$T_A = 25°C$, B = 0 G		1.625	1.65	1.675	V
Delta QVO	$\Delta V_{OUT(Q)}$	A1304ELHLX-T	$T_A = 85°C$, relative to QVO at 25°C	–	±40	–	mV
		A1304ELHLX-05-T		–	±40	–	mV
Ratiometry Quiescent Voltage Output Error	$Rat_{VOUT(Q)}$	Across specified supply voltage range (relative to $V_{CC} = 3.3$ V)		–	±1.5	–	%
Ratiometry Sensitivity Error	Rat_{Sens}	Across specified supply voltage range (relative to $V_{CC} = 3.3$ V)		–	±1.5	–	%
Linearity Sensitivity Error	Lin_{ERR}	A1304ELHLX-T	Typ. Sensitivity, ±300 G	–	±1.5	–	%
		A1304ELHLX-05-T	Typ. Sensitivity, ±2250 G	–	±1.5	–	
Sensitivity Drift Due to Package Hysteresis	$\Delta Sens_{PKG}$	$T_A = 25°C$, after temperature cycling		–	±2	–	%
Magnetic Field Range	B	A1304ELHLX-T	Range of Input Field	–	±375	–	G
		A1304ELHLX-05-T		–	±3000	–	

CHARACTERISTIC DEFINITIONS

Sensitivity The amount of the output voltage change is proportional to the magnitude and polarity of the magnetic field applied. This proportionality is specified as the magnetic sensitivity, Sens (mV/G), of the device and is defined as:

$$\mathrm{Sens} = \frac{V_{OUT(B+)} - V_{OUT(B-)}}{(B+) - (B-)} \qquad (2)$$

where B+ is the magnetic flux density in a positive field (south polarity) and B– is the magnetic flux density in a negative field (north polarity).

Sensitivity Temperature Coefficient The device sensitivity changes as temperature changes, with respect to its Sensitivity Temperature Coefficient, TC_{SENS}. TC_{SENS} is defined as:

$$TC_{Sens} = \left(\frac{Sens_{T2} - Sens_{T1}}{Sens_{T1}} \times 100\right)\left(\frac{1}{T2 - T1}\right) \quad (\%/°C) \qquad (3)$$

where T1 is the baseline Sens programming temperature of 25°C, and T2 is the sensitivity at another temperature.

The ideal value of Sens across the full ambient temperature range, $Sens_{IDEAL(TA)}$, is defined as:

$$Sens_{IDEAL(TA)} = Sens_{T1} \times [100\ (\%) + TC_{SENS}\,(T_A - T1)] \qquad (4)$$