

Magnetoresistance (MR) Transducers

And How to Use Them as Sensors

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Perry A. Holman, Ph.D.

Acronyms

AMR	Anisotropic Magnetoresistance (interchangeable with MR)
EA	Easy Axis
GMR	Giant Magnetoresistance
HA	Hard Axis
HDD	Hard Disk Drive
MR	Magnetoresistance (interchangeable with AMR)

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Magnetic Sensors

Three main types of magnetic sensor technology are discussed within these notes: Hall Effect, Magnetoresistance (AMR or MR), and Giant Magnetoresistance. The different technologies are compared and contrasted, with emphasis on magnetoresistance.

1.1 BRIEF BACKGROUND ON MAGNETIC SENSORS

1.1.1 Hall Effect

Edwin Hall discovered the effect named for him in 1879. He found that an applied magnetic field created a voltage perpendicularly to the typical voltage on a thin sheet of gold. Honeywell, Micro Switch division (now Sensing and Control) created the first practical semiconductor Hall effect device, in 1965. The initial application was computer keyboards. Honeywell now produces millions of Hall effect devices a year for a variety of sensing applications, such as gear tooth, wheelspeed, and linear position.

1.1.2 Magnetoresistance

In 1857, William Thomson (also known as Lord Kelvin, of Kelvin temperature scale fame) found that the resistance of iron changes when it is magnetized. This property, where the electrical resistance of a metal changes with an applied magnetic field is known as magnetoresistance (MR). As of the 1960's, vacuum technology improved

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to the point that very pure, extremely small, films of materials were applied on a substrate, such as silicon or glass. Some of the earliest applications of thin magnetic films were for memory devices, such as bubble memory and hard disk drives (HDD). Honeywell is a major manufacturer of MR sensors for commercial, industrial, and automotive applications. The main type of MR material utilized is Permalloy, an 80% nickel, 20% iron alloy.

1.1.3 Giant Magnetoresistance

The Giant Magnetoresistance effect (GMR) was not created experimentally until 1988. GMR devices are created by stacking very thin (~ 1 nanometer) films of different types of materials, such as permalloy and copper. The term giant comes from GMR materials showing a much larger signal (3 to 5 times) compared to MR, but requiring more magnetic field. The main usage of GMR sensors is for modern, high density hard disk drives.

1.2 COMPARISON OF MAGNETIC SENSING TECHNOLOGIES

This section will attempt to briefly explain some differences between the major magnetic sensing technologies. Please understand the brevity of the explanation, and that limitations will arise from this incomplete summary.

1.2.1 Hall Compare

Hall effect devices have been commercially available for the longest time, so should be the best understood. Hall devices are linear: double the input, the output doubles. Hall is the least expensive to implement in an integrated sensor (electronics on the same chip as the sensor). The reason for this is the epitaxial material most transistors are created in, is utilized directly for the Hall element. Also, the size is typically quite small. There are some downsides to Hall devices. The signal from a Hall element is very small (a few microvolts). Offsets over temperature are typically the highest with Hall. Since the Hall is piezoresistive (pressure sensitive), packaging stress causes offsets, negatively affecting the capability of the sensors. Luckily, circuit techniques exist which can improve the situation, with additional circuit complexity. Hall devices are typically sensitive to a magnetic field perpendicular to the chip. If there is a chip on a table, the Hall is sensitive to a field out of the table.

1.2.2 MR Compare

Magnetoresistive devices have been commercially available for several decades, and have been on automobiles for many years. Thus, MR has reached a level of maturity. MR devices have a non-linear output, which saturates: double the input, perhaps no change in output. Permalloy typically exhibits a $\cos^2(\theta)$ relationship. Permalloy is

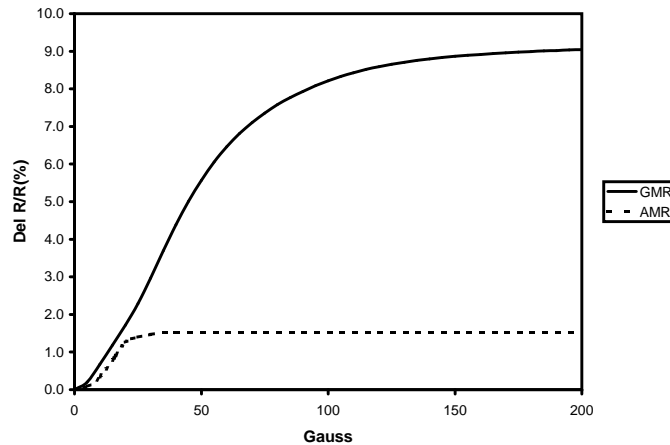


Fig. 1.1 GMR and MR Curve.

relatively inexpensive to implement in an integrated sensor, requiring only one extra processing step. Honeywell has the patent on a method of integrating permalloy with electronics. Additionally, this patent (US 5,557,879) gives an advantage for protecting the magnetic film in harsh (ie. automotive) environments. Permalloy has a large content of iron, and iron rusts. In harsh environments, this will degrade performance, and potentially cause catastrophic failures. The signal is large with MR, approaching 3% maximum signal change. Offsets are typically low, no piezoresistance. MR is sensitive to magnetic field in the plane of the chip. Chip on a table, MR is only sensitive to a magnetic field along the surface of the table.

Furthermore, a permalloy sensor may only have the permalloy device on a chip, ie. no electronics, and thus is very low cost (but requiring additional external circuits).

1.2.3 GMR Compare

Giant magnetoresistive devices have been available for only a short time, and thus not as proven long term reliability. The main application of GMR is for hard disk drives. GMR devices have a non-linear output, which saturates, similar to MR. GMR also usually exhibits a $\cos^2(\theta)$ relationship. Please note that since GMR is a stack of different materials, device designers have many design parameters (different materials, number of layers, thickness of layers, etc.), so GMR materials may be designed for different applications. In other words, there is no GMR material, the term is used for a wide range of “stacks” of materials. Since there is more processing, GMR tends to be more expensive than permalloy. Additionally, GMR devices are typically not integrated with electronics. The signal with GMR may be huge, over 10%, and may be as sensitive as permalloy. Often there is a trade-off: more total signal, less sensitive. GMR is sensitive in the same plane as MR. Fig. 1.1 shows a plot of the response of a GMR device compared to a permalloy device.

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Table 1.1 gives a comparison of MR, GMR and Hall:

Table 1.1 Comparison of MR, GMR and Hall versus MR.

Parameter	MR	GMR	Hall
Maturity	Mature	New	Very Mature
Linearity	Non-linear	Non-linear	Linear
Complexity	1 Extra Step	Very	Simple
Integration	Typically	Rarely	Always
Offset	Low	Low	Piezo-resistive
Signal Size	3%	10+%	Small
Sensitive	In Plane	In Plane	Perpendicular

1.3 HONEYWELL DIFFERENTIATION

Honeywell provides differentiation as a sensor supplier, including magnetoresistor sensors. In addition to a global presence, Honeywell MR sensors have a wealth of technical advantages. First, Honeywell has many years of design expertise, to develop a sensor specific for customer needs. Next, Honeywell has a proven track record of reliability in sensors, demonstrated by millions of sensors in automotive under-the-hood applications. Honeywell is a Tier 1 supplier to many automotive OEMs. This reliability stems from patented processing, which improves long-term reliability. Finally, Honeywell technology allows integration of the MR sensing element, and the electronics, to provide the lowest sensor cost, compared to separate sensor and electronics. Table 1.2 summarizes Honeywell’s advantages in MR sensors.

Table 1.2 Honeywell MR Advantages.

Global Presence
Design Expertise
Customer Specific Design
High Reliability
Automotive Harsh Environment
Tier 1 Automotive Supplier
Long-Term Reliability, Patent Process
Integrated Sensor and Electronics, lowest system cost

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Applications

Within this chapter, several applications are discussed, to give the reader some ideas.

2.1 CURRENT

Current is an important electrical value to measure. One of the simplest methods is an in line current meter, but this requires the line to be broken, and current meters are sometimes expensive. Another method is to place a small resistor ($< 1\Omega$) in line, and measure the voltage across this resistor, referred to as a sense resistor. A potential issue is that power is lost in the sense resistor. For some applications, an alternative with advantages is a non-invasive current sensor. To begin the conversation, remember that a current carrying wire creates a field. Thus, a current in a wire creates “circles” of magnetic field (Fig. 2.1), where the amplitude falls off with a $1/r$ relationship, and the direction follows the right-hand-rule. Since the sensor is small, on the order of less than a millimeter, the field is essentially uniform, Fig. 2.2. The resistor should be placed to maximize the response to the field from the wire (Fig. 2.3).

2.2 SPEED

This section talks about speed sensors, specifically a rotating ring magnet, such as anti-lock brakes. The general concept is a ring magnet, which is a disk, covered by

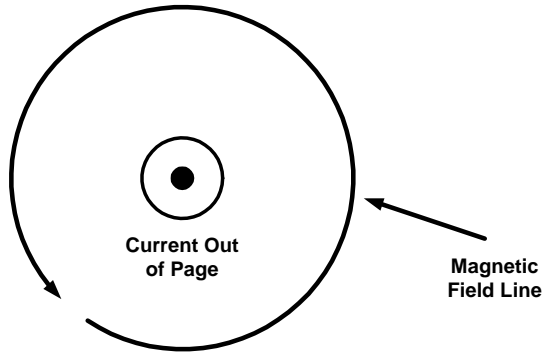


Fig. 2.1 Magnetic Field Lines.

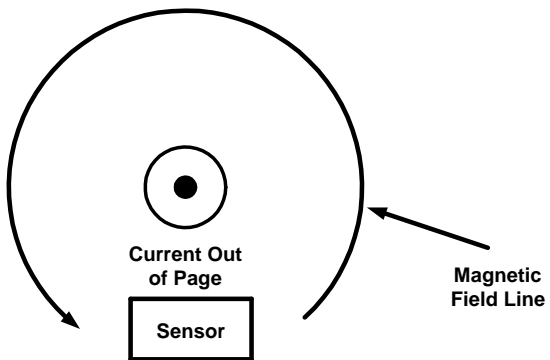


Fig. 2.2 Magnetic Field Lines with Sensor.

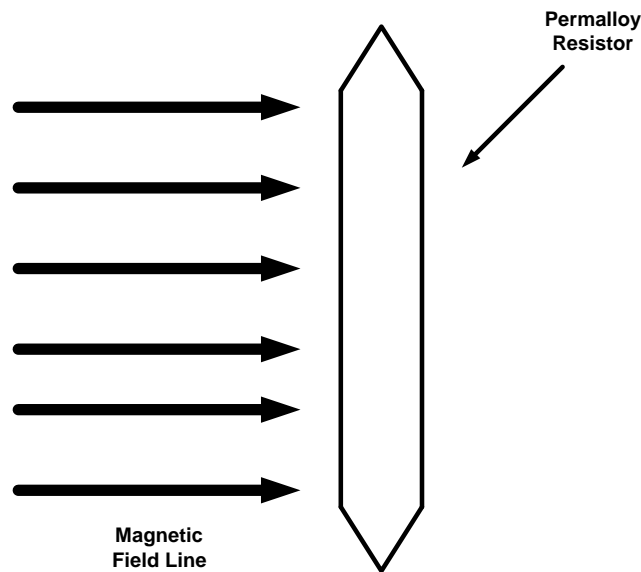


Fig. 2.3 Permalloy Resistor with Perpendicular Field.

permanent magnet material on the outer portion. Two main version are considered: edge-on and face-on detection.

2.2.1 Edge-On

Edge-on detection is performed with the edge of the sensor near the rotating ring magnet. Edge-on usually does not allow as large of airgap as face-on. The field from the ring magnet gives a field in a direction, as well as a rotating field, depending on airgap, Fig. 2.4. Edge-on devices may utilize a “diamond” bridge, to minimize the effect of “chirp” (Fig. 2.5). This bridge configuration tends to use the rotating magnetization, instead of hard axis response.

2.2.2 Face-On

Face-on sensing is performed with the face of the sensor near to the edge of the ring magnet. Typically, face-on senses at the greatest airgap, (Fig. 2.6).

2.3 GEARTOOTH

Geartooth sensors are named for the targets to be sensed, which have teeth, and appear similar to a gear. A geartooth sensor has a magnet within the sensor, as opposed to ring magnet sensor, where the sensor is the magnet. The magnet integrated in the

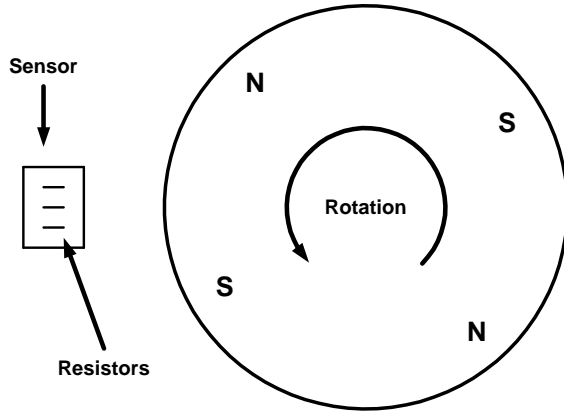


Fig. 2.4 Speed Sensor, Edge On Configuration.

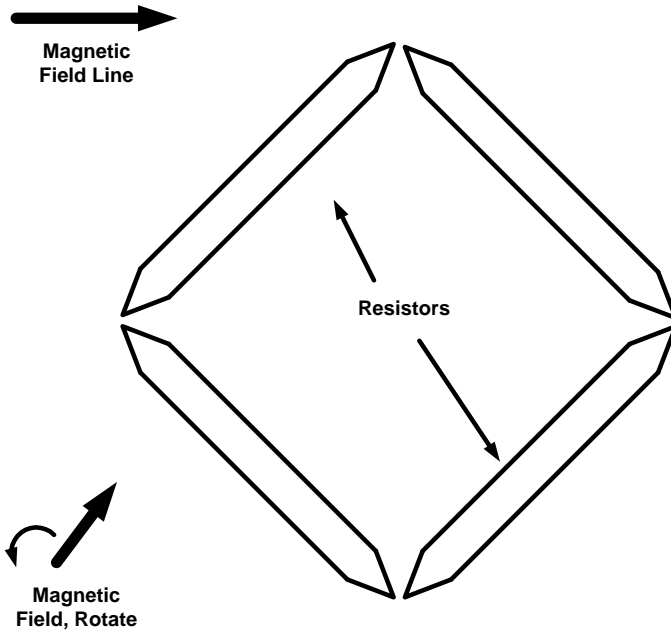


Fig. 2.5 "Diamond" Configuration Bridge.

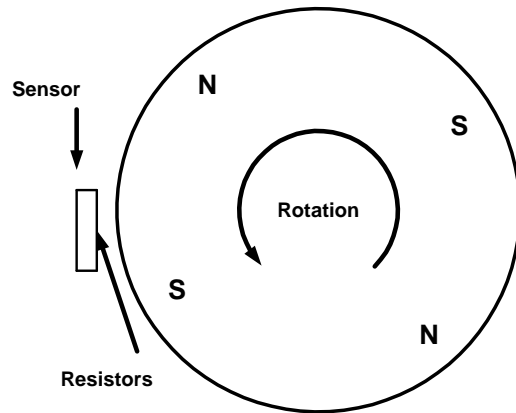


Fig. 2.6 Speed Sensor, Face On Configuration.

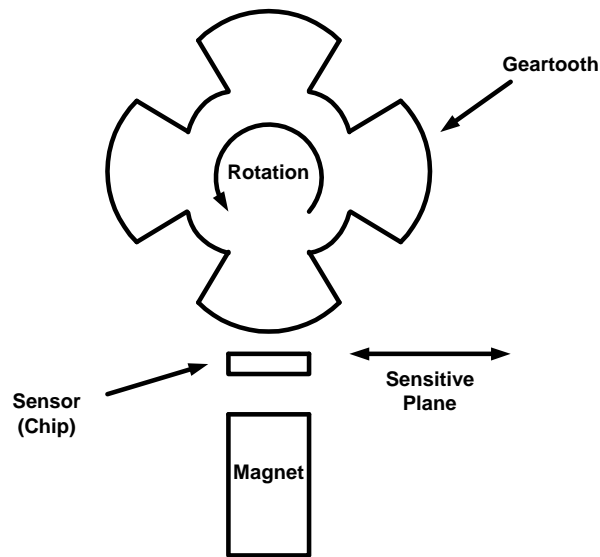


Fig. 2.7 Geartooth Sensor.

geartooth sensor creates a magnetic field, and the target is ferromagnetic. The target modifies the magnetic field, changing the flux at the sensor. This change in flux creates a change in resistance of the sensor, giving a signal. This signal is related to the position of the teeth as the target rotates around, which is an indication of the position of the pistons in the cylinders, Fig. 2.7

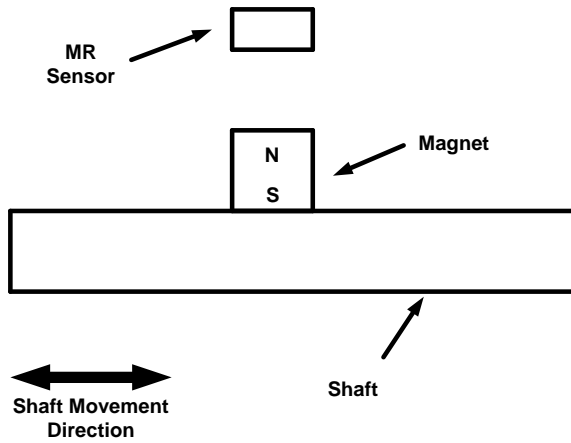


Fig. 2.8 Linear Position System.

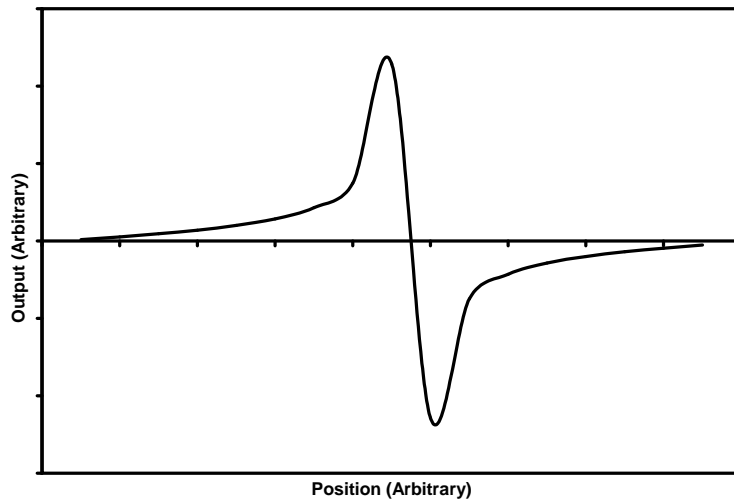


Fig. 2.9 Linear Application Sensor Output Example.

2.4 LINEAR POSITION

Another important measurement is linear position, for example, the location of a shaft. A magnet can be attached to the device of interest, and a MR sensor placed near the magnet, Fig. 2.8. As the shaft moves past the MR sensor, a signal is produced, such as Fig. 2.9. A typical linear position bridge might appear as Fig. 2.10. An array of sensors are often utilized in a Honeywell patented (such as US 5,589,769) system, to measure linear position to a high resolution.

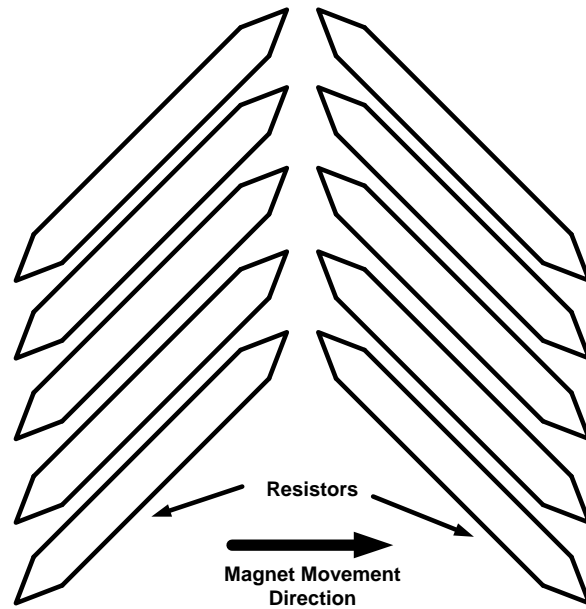


Fig. 2.10 Linear Application Bridge.

2.5 ANGLE POSITION

Angle position sensors are utilized to measure the rotary position of a device, for example, a steering wheel. As mentioned above, permalloy has a response ($\Delta R/R$) which is $\cos^2(\theta)$. Also, $\cos(\theta - 90^\circ) = \sin(\theta)$, and since permalloy is an even function material, 45° physical degrees gives a sin versus cos. So, bridge 1 gives an output that is a representative of $\sin^2 \theta$, and bridge 2 is the $\cos^2 \theta$, thus, some processing provides the angle (θ). Permalloy angle position sensors are limited to a range of $\pm 90^\circ$, because the function is even ($\cos^2 \theta$).

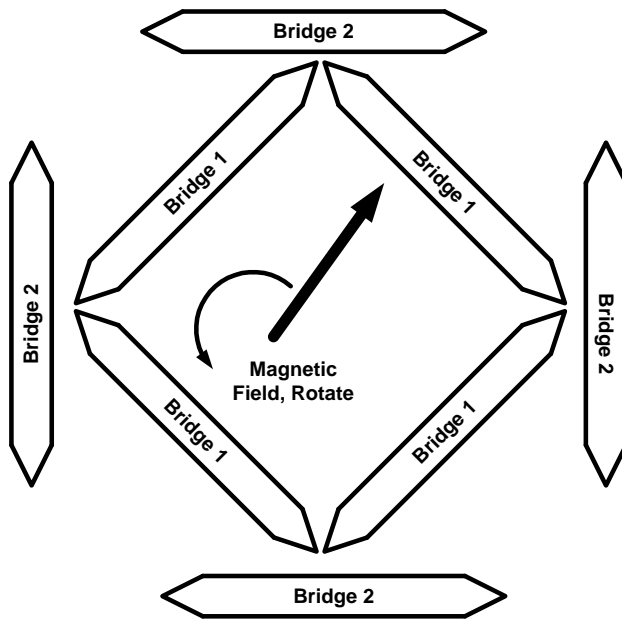


Fig. 2.11 Rotary Application Bridge.

Appendix A

Units and Conversions

A.1 MAGNETIC UNITS

Quantity	Symbol	Unit, CGS	Unit, SI	(SI)/(CGS)Ratio*
Length	L	centimeter, cm	meter, m	10^2
Mass	M	gram, g	kilogram, kg	10^3
Time	t	second, s	second, s	1
Magnetic Flux	Φ	maxwell	weber, Wb	10^8
Magnetic Flux Density	B	gauss, G	tesla, T	10^4
Magnetic Field Strength	H	oersted, Oe	ampere/meter, A/m	$4\pi/10^3$
Magnetomotive Force	F	gilbert, Gb	ampere, A	$4\pi/10$
Permeability of Freespace	μ_o	(unity)	henry/meter, H/m	$10^7/4\pi$
Reluctance	\mathcal{R}	gilbert/maxwell	1/henry, H^{-1}	$4\pi/10^9$
Permeance	P	maxwell/gilbert	henry, H	$10^9/4\pi$

(* Quantity in SI units must be multiplied by this ratio to convert to CGS units.)

A.2 ELECTRICAL UNITS

Quantity	Symbol	Name	Abbr.
Current	I or i *	ampere	A or a
Charge	Q or q *	coulomb	C
Voltage	V or v *	volt	V or v *
Power	P	watt	W or w
Resistance	R **	Ohm	Ω
Reactance	X **	Ohm	Ω
Impedance	Z **	Ohm	Ω
Conductance	G **	Mho or Siemens	$\bar{\Omega}$
Admittance	Y **	Mho or Siemens	$\bar{\Omega}$
Susceptance	B **	Mho or Siemens	$\bar{\Omega}$
Capacitance	C	Farad	F or f
Inductance	L	Henry	H or h
Frequency	F or f	Hertz	Hz
Period	T	seconds	s

* Capital letter general used for peak RMS or DC value; small letter used for instantaneous values.

** Small letter generally used for the internal value of a component.

A.3 STANDARD SI UNIT PREFIXES

Prefix	Abbr.	Meaning	Prefix	Abbr.	Meaning
yocto-	y-	10^{-24}	deka-	da-	10^1
zepto-	z-	10^{-21}	hecto-	h-	10^2
atto-	a-	10^{-18}	√ kilo-	k-	10^3
femto-	f-	10^{-15}	√ mega-	M-	10^6
√ pico-	p-	10^{-12}	√ giga-	G-	10^9
√ nano-	n-	10^{-9}	tera-	T-	10^{12}
√ micro-	μ -	10^{-6}	peta-	P-	10^{15}
√ milli-	m-	10^{-3}	exa-	E-	10^{18}
√ centi-	c-	10^{-2}	zetta-	Z-	10^{21}
deci-	d-	10^{-1}	yotta-	Y-	10^{24}

(√ means often utilized)

Glossary

Anisotropic Anisotropic is a term often discussed with permalloy. The best way to describe anisotropic, is by comparison. The opposite of isotropic is anisotropic. Isotropic simply means the same in every direction. Thus, anisotropic means that it depends on the direction. For permalloy, the magnetoresistance is dependent on the direction of the applied field.

Barber-pole A permalloy device, with shorting bars, to have the current at 45° to the magnetization, with zero applied field. This configuration is very sensitive at low magnetic field values, and are used a magnetometer (for a compass), or road edge detection for automated highways.

Coercivity The externally applied magnetic field required to bring the resultant (of the externally applied, and intrinsic field from the material) to zero.

Easy Axis Easy Axis is the preferred direction of magnetization of a film, created during the deposition of the film on a wafer. Typically, the mechanical length of the resistor, and electrical current flow, is generally in the direction of the Easy Axis.

Hard Axis Hard Axis is generally perpendicular to the Easy Axis, typically across the short (narrow) dimension of a resistor.

Magnetometer A device for sensing low magnetic field values, and direction. Often utilized for compasses.

PPM Parts per million is a convenient term for small changes, such as temperature coefficient of resistance (TCR). 10,000 ppm/°C equals 1%/°C.

Quadrature When two signals are out of phase of 90° . This allows margin to tell which signal is leading or lagging.

Right-Hand Rule A simple method of determining the effect of certain types of actions. Take the right hand, if the action of rotating the fingers points the thumb up, then, the reaction is in the direction of the thumb. For a simple example, most mechanical screws are right-hand rule, so if the screw is rotated counter clockwise, the screw follows the thumb, and will be driven into the direction of the thumb.

TCR Temperature Coefficient of Resistance. The electrical resistance of a material is often a function of temperature. Most metals have a positive TCR, ie. the resistance increases at higher temperatures. TCR is often given in percent change per degree Centigrade ($\%/^\circ\text{C}$), or if the value is small, TCR is often in parts per million per degree Centigrade ($\text{ppm}/^\circ\text{C}$), also see PPM.