Semiconductor Sensors:

Ch3: Electromagnetic Sensors cont.

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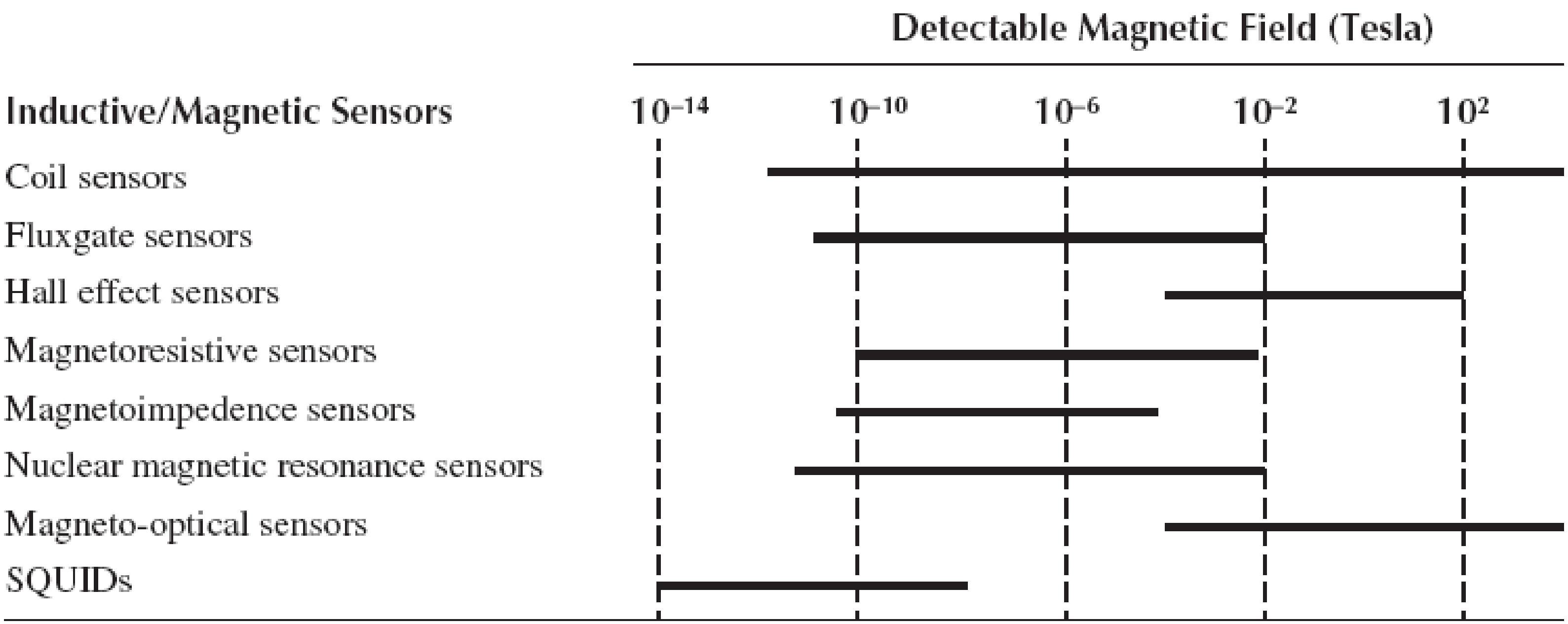
مقایسه حسگرهای مغناطیسی از نظر محدوده کارکرد:

TABLE 5.1
Magnetic Field Detection Ranges of Inductive and Magnetic Sensors



حسگرهای شارگیت (Fluxgate):

The fluxgate sensor known from 1936 (Aschennbrener et al. 1936) is still commonly used due to many advantages: resolution starting from 1pT, alternating signal modulated by low-frequency signal proportional to measured magnetic field—this way noise and offset can be relatively easy suppressed.

Operating of such sensor is based on the fact that the magnetizing curve is nonlinear (with saturation) and symmetrical. If we magnetize the ferromagnetic material periodically with magnetic field *H* significantly larger than "knee" of the magnetization curve, we obtain the distorted flux density (signal A). But due to symmetry of the magnetization curve, this signal contains only odd harmonics. When additional external magnetic field *Hx* appears, then the magnetization curve becomes asymmetrical this causes presence of even harmonics in the output signal. Usually, the second harmonic is used as the signal proportional to external magnetic field *Hx*.

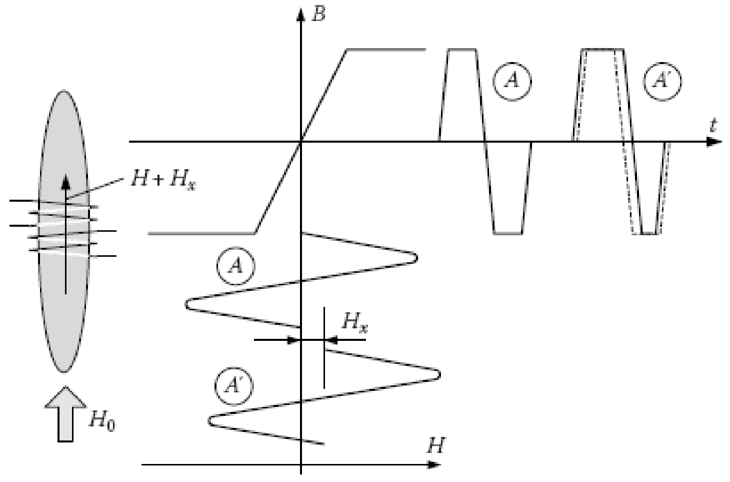


FIGURE 4.50
Principle of operation of the fluxgate sensor.

حسگرهای شارگیت (Fluxgate):

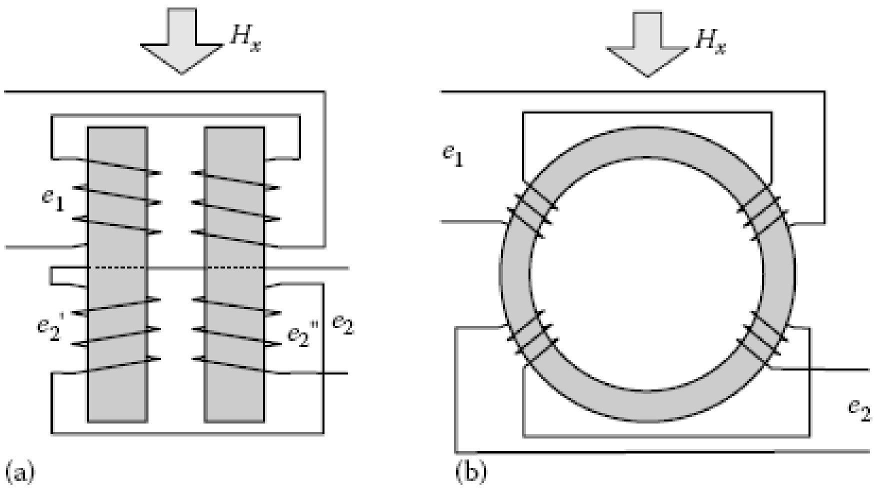


FIGURE 4.51
A fluxgate sensor with two rod cores (a) and ring core fluxgate sensor (b) (bright).

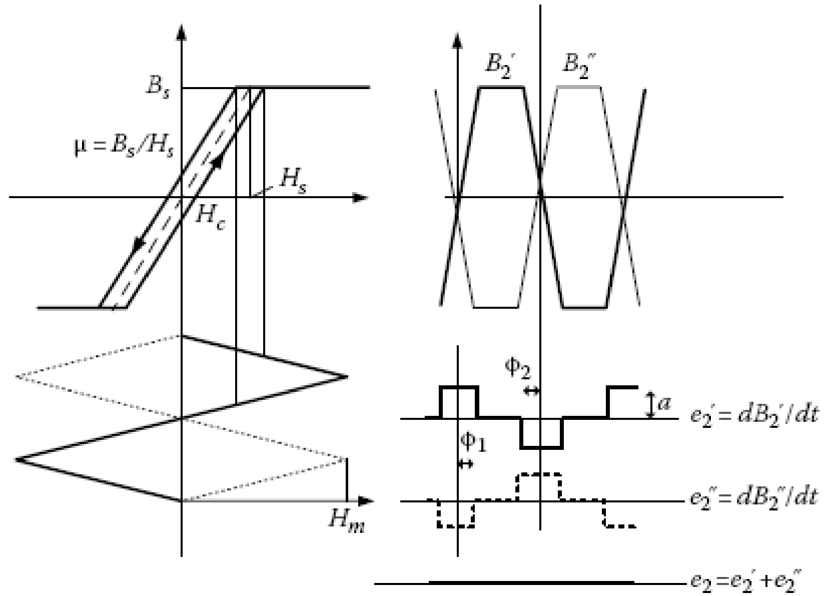


FIGURE 4.52
Signals in fluxgate sensor for $H_x = 0$.

Considering the sensor with the core represented by simplified hysteresis shape and the exciting signal by a simplified triangular shape (Figure 4.52). The output signal in secondary coil with *n*2 turns wound on the core with area *A* is:

$$e_2 = -An_2 \frac{dB}{dt} = 0.$$

حسگرهای شارگیت (Fluxgate):

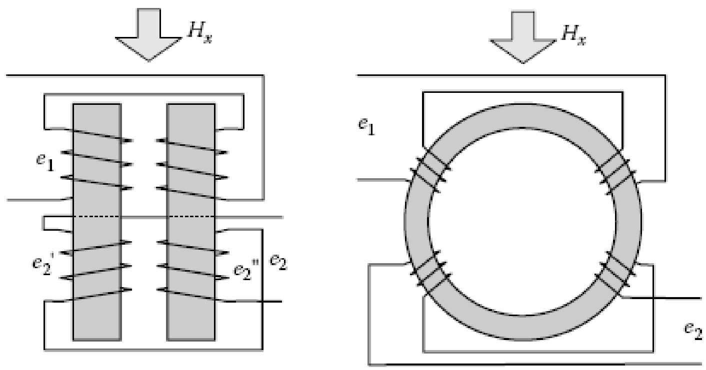


FIGURE 4.51
A fluxgate sensor with two rod cores (a) and ring core fluxgate sensor (b) (bright).

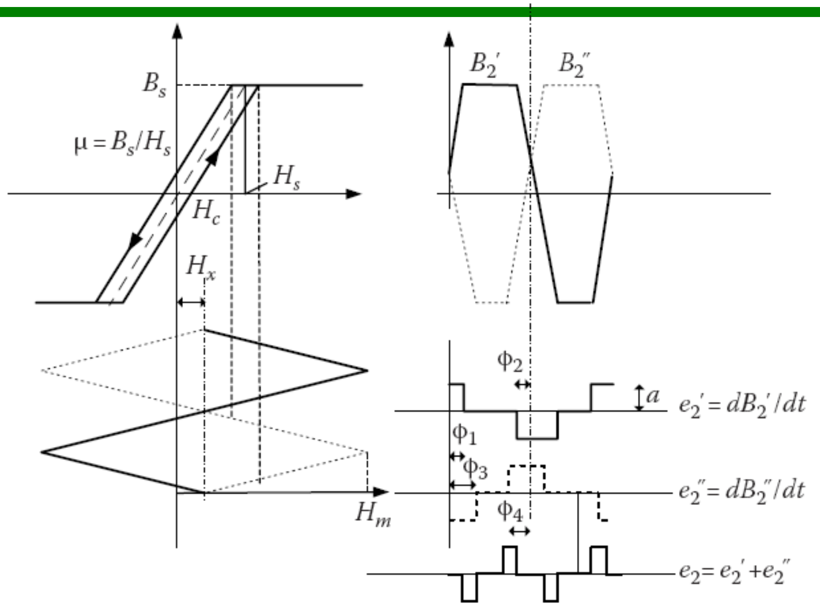


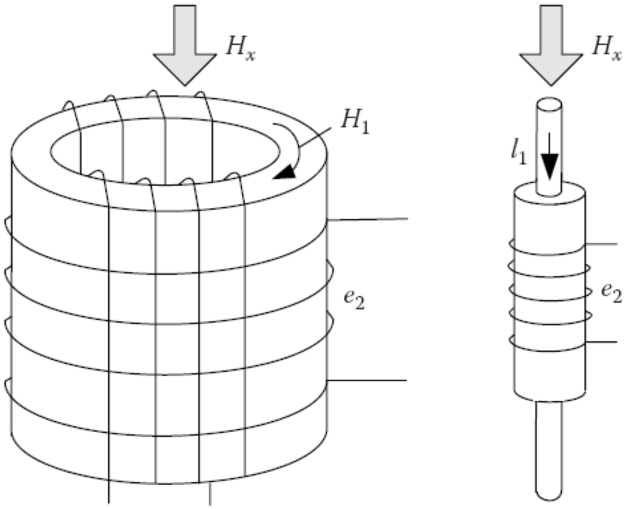
FIGURE 4.53
Signals in a fluxgate sensor for some external field H_x.

$$e_2 = e_2' + e_2'' = 16 n_2 f A \mu H_x \sin \pi \frac{H_s}{H_m} \sin\left(2\omega t - \pi \frac{H_c}{H_m}\right) + \mathrm{L}$$

Thus, the odd harmonics are eliminated and the output comprises only even harmonics. The magnitude of the second harmonic output signal is:

$$E_2 = 16 n_2 f A \mu H_x \sin \pi \frac{H_s}{H_m}$$

حسگر شارگیت (Fluxgate)- نوع متعامد:



FIGUR E 4.54
Orthogonal type fluxgate sensors.

In these sensors, the two coils: exciting and pick-up are perpendicular to each other and in the absence of external magnetic field the output signal is equal to zero. Any external magnetic field is added to the exciting field and the resultant magnetic field,

$$H_w = \sqrt{H_x^2 + \left(H_m \sin \omega t\right)^2}$$

saturates the core periodically. As a result, the output second harmonic component is proportional to the external measured field.
Sensors of this type were proposed many years ago (Alldredge 1951), but recently they are studied again because they can be very small and fabricated with thinfilm technology (Fan et al. 2006, Zhao et al. 2007).

حسگرهای مقاومت مغناطیسی(Magnetoresistor):

The magnetoresistive (MR) effect (change of resistance caused by magnetic field) exists practically in all metals but it is detectable only at very low temperature and in high magnetic field. However, there are several materials for which the MR effect is sufficiently large at room temperature: ferromagnetic metals, semiconductors, and some minerals as bismuth or lanthanum-based oxides. The MR effect can be large in some artificial multilayer structures like valve or superlattices.

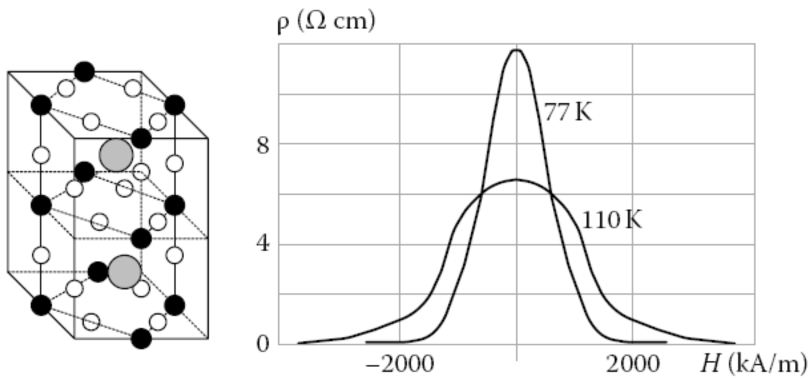


FIGURE 4.74
The crystal structure of manganate perovskites $La_{67}Ca_{33}MnO_3$ and its change of resistance versus magnetic field. (From McCormack, M. et al., *Appl. Phys. Lett.*, 64, 3045, 1994.)

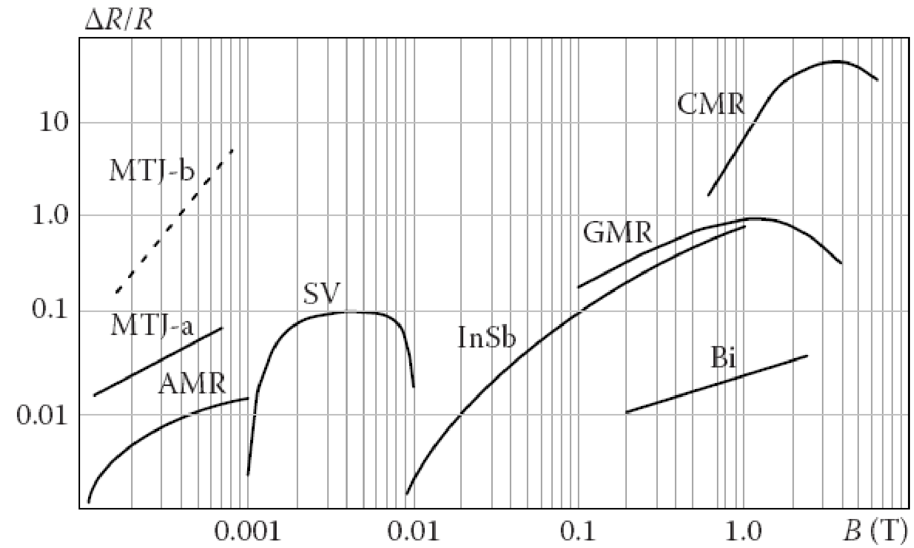


FIGURE 4.73
The main magnetoresistive effects: MTJ, magnetic tunnel junction; AMR, anisotropic magnetoresistance; SV, spin valve; InSb, semiconductor magnetoresistors; GMR, giant multilayer magnetoresistance; Bi, bismuth; CMR, collosal magnetoresistance.

حسگرهای مقاومت مغناطیسی (Magnetoresistor):

In magnetoresistance (MR) effect, a conductor changes its electric resistance in the presence of an external magnetic field. The MR effect was discovered by William Thomson (*Lord Kelvin*) in 1856. He found that iron and nickel exhibited a small increase in electrical resistance along the direction of an applied magnetic field and a similar decrease in resistance in the transverse direction. The magnitude of the effect, *MR* (unitless), depends on the material of the conductor as:

$$M_R = \frac{\rho_B - \rho_0}{\rho_0} \times 100\%$$

where ρB (in $\Omega \cdot m$) is the resistivity of the conductor under an applied magnetic field *B*, and $\rho 0$ (in $\Omega \cdot m$) is the resistivity of the conductor without an applied magnetic field *B*.

EXAMPLE 5.6

Under an applied magnetic field $B = 0.75$ T, an iron (Fe) conductor changes its resistivity from $\rho_0 = 10$ ($\mu\Omega \cdot$ cm) to $\rho_{0.75} = 10.53$ ($\mu\Omega \cdot$ cm); while a nickel (Ni) conductor (with the same size and shape as the iron conductor) changes its resistivity from $\rho_0 = 6.99$ ($\mu\Omega \cdot$ cm) to $\rho_{0.75} = 7.07$ ($\mu\Omega \cdot$ cm). Which material displays a stronger magnetoresistance effect?

Solution

For Fe:

$$M_R = \frac{10.53 - 10}{10} = 0.053 \quad \text{or } 5.3\%$$

For Ni:

$$M_R = \frac{7.07 - 6.99}{6.99} = 0.011 \quad \text{or } 1.1\%$$

Thus, iron demonstrates a stronger MR effect.

انواع حسگرهای مقاومت مغناطیسی:

On the basis of the materials and structures, MR effects can be classified as:

1. *Ordinary magnetoresistance* (OMR) effect in nonmagnetic metals;
2. *Anisotropic magnetoresistance* (AMR) effect in ferromagnetic alloys;
3. *Giant magnetoresistance* (GMR) effect in multiple alternating ferromagnetic-alloy and metallic layer structures;
4. *Tunneling magnetoresistance* (TMR) effect in multiple alternating ferromagnetic-alloy and thin-insulating layer structures;
5. *Ballistic magnetoresistance* (BMR) effect in multiple alternating ferromagnetic-alloy-layer and nonferromagnetic-point structures; and
6. *Colossal magnetoresistance* (CMR) effect in $La_{1-x}M_xMnO_3$ (M = Ca or Sr) perovskite structures.

مقاومت مغناطیسی نوع OMR:

OMR effect is present in normal (nonmagnetic) metals. It arises from the effect of Lorentz force acting on an electron in a magnetic field, causing a circular or helical motion of the electron. OMR has not found much practical applications yet due to its very low MR effect (<1%).

حسگر مقاومت مغناطیسی نوع AMR:

Anisotropic Magnetoresistance (AMR) Effect

AMR, discovered in 1857 by William Thomson, is a typical effect in ferromagnetic (FM) materials. The term *anisotropic* is from the dependence of the resistivity on the orientation of the magnetic field relative to the current direction Θ. Mathematically it is expressed by:

$$\rho(\Theta) = \rho_0 + \Delta\rho\cos^2\Theta \tag{5.12}$$

where ρ_0 is the resistivity of the material without an applied magnetic field, and $\Delta\rho$ $(= \rho(0^\circ) - \rho(90^\circ))$ is the resistivity difference between the parallel $(\Theta = 0^\circ)$ and perpendicular $(\Theta = 90^\circ)$ relationship between the current direction and the applied magnetic field direction.

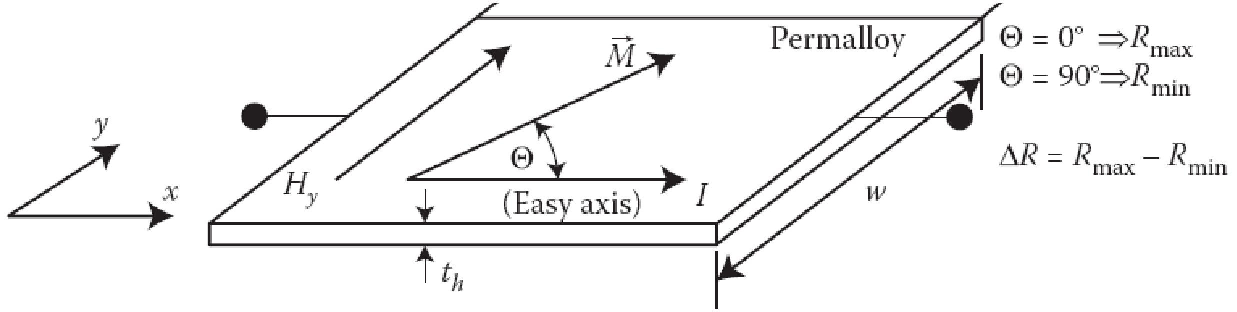


FIGURE 5.15 The MR effect in permalloy.

حسگر مقاومت مغناطیسی نوع AMR:

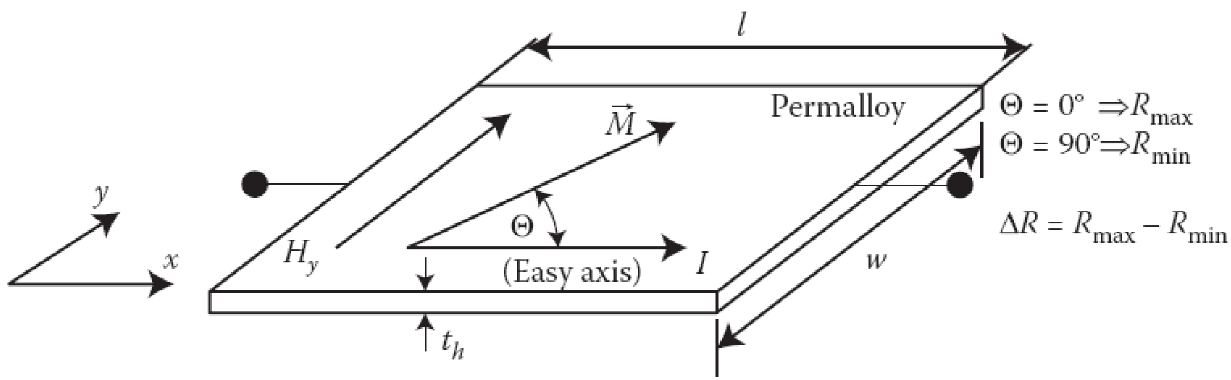


FIGURE 5.15 The MR effect in permalloy.

During the deposition process of the strip manufacturing, a strong magnetic field is applied to magnetize and define the *preferred* (*internal*) *magnetization direction* (parallel to the length of the trip—the *x*-axis) for the strip. After the manufacturing process is finished, this magnetic field is removed, and the strip (sensor) will maintain its magnetization in the *x* direction (called *easy axis*) due to its ferromagnetic properties.

The dependence of the sensor resistance R on the angle Θ is described by [8]:

$$R(\Theta) = \underbrace{\rho_{\perp}\frac{l}{wt_h}}_{R_0} + \underbrace{(\rho_{//} - \rho_{\perp})\frac{l}{wt_h}}_{\Delta R}\cos^2\Theta = R_0 + (\underbrace{R_{max} - R_{min}}_{\Delta R})\cos^2\Theta \qquad (5.13)$$

حسگر مقاومت مغناطیسی نوع AMR:

$$R(\Theta) = R_{\min} \sin^2 \Theta + R_{\max} \cos^2 \Theta \tag{5.14}$$

The angle Θ directly relates to the strength of the external magnetic field H_y:

$$\cos^2 \Theta = 1 - \left(\frac{H_y}{H_{\max}} \right)^2 \quad \text{or} \quad \sin^2 \Theta = \left(\frac{H_y}{H_{\max}} \right)^2 \tag{5.15}$$

Thus,

$$R(H_y) = R_0 + (R_{\max} - R_{\min}) \left[1 - \left(\frac{H_y}{H_{\max}} \right)^2 \right] \quad (H_y \leq H_{\max}) \tag{5.16}$$

where $H_{\max}$ is the maximum field strength that an AMR sensor can sense before saturation, and it is a parameter of material and geometry of the sensor. For $H_y > H_{\max}$, R equals R_0.

حسگر مقاومت مغناطیسی نوع AMR:

EXAMPLE 5.8

Find the resistance change of an AMR sensor when an external magnetic field strength $H_y = 3\ \text{kA}\cdot\text{m}^{-1}$ is applied perpendicular to the AMR's easy axis, knowing $H_{max} = 10\ \text{kA}\cdot\text{m}^{-1}$, $R_{max} - R_{min} = 400\ \Omega$.

SOLUTION

When no external magnetic field is applied ($H_y = 0$):

$$R(0) = R_0 + (R_{max} - R_{min})\left[1 - \left(\frac{0}{H_{max}}\right)^2\right] = R_{max}$$

When the external magnetic field is applied ($H_y \neq 0$):

$$\begin{aligned} R(H_y) &= R_0 + (R_{max} - R_{min})\left[1 - \left(\frac{H_y}{H_{max}}\right)^2\right] = R_{min} + (400\ \Omega)\left[1 - \left(\frac{3\times 10^3\ \text{A}\cdot\text{m}^{-1}}{10\times 10^3\ \text{A}\cdot\text{m}^{-1}}\right)^2\right] \\ &= R_{min} + 364\ \Omega \end{aligned}$$

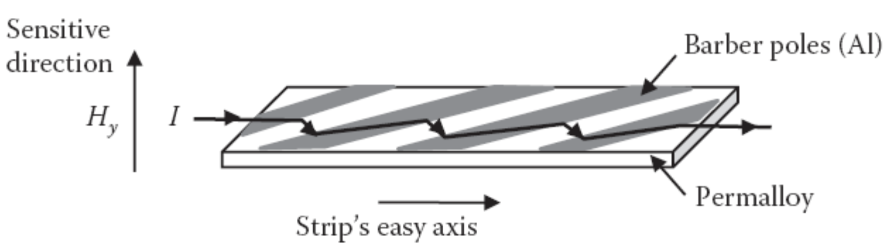
The resistance change is:

$$R(0) - R(H_y) = R_{max} - (R_{min} + 364\ \Omega) = 400\ \Omega - 364\ \Omega = 36\ \Omega$$

حسگر مقاومت مغناطیسی نوع AMR:

Barber poles Technics:

A standard AMR sensor is composed of a nickel–iron (permalloy) resistive thin film deposited as a strip on a silicon wafer. An improved structure is to deposit aluminum stripes (called *barber poles*) on the top of the permalloy strip at an angle of 45° to the strip's easy axis. Since the conductivity of aluminum is much higher than permalloy, the electrons tend to flow as much as they can along the aluminum strips and as less as they can along the permallery strips, resulting an effect of the current's rotating 45°.



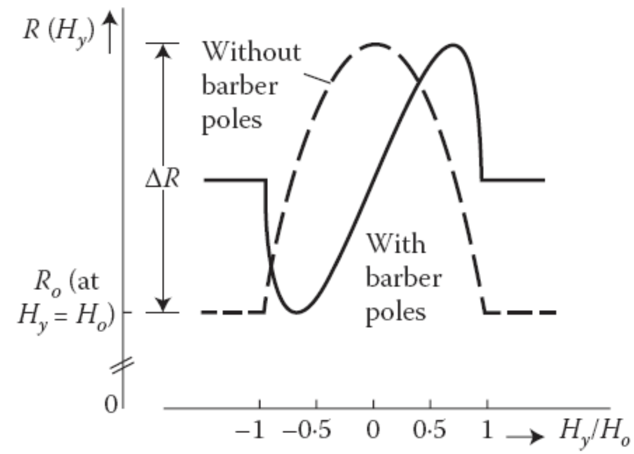


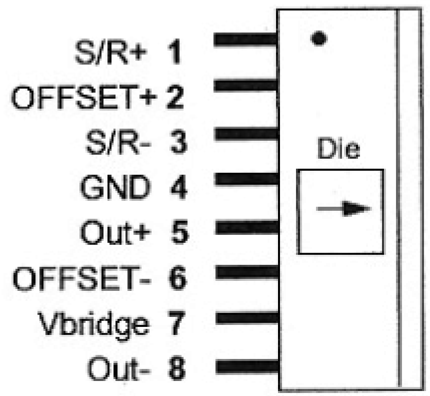
FIGURE 5.19 The *R*–*H* characteristics of a standard sensor and a Barber-pole sensor.

$$R(H_y) = R_0 + \frac{\Delta R}{2} \pm \Delta R \frac{H_y}{H_{max}} \sqrt{1 - \left(\frac{H_y}{H_{max}}\right)^2}$$

The sensor displays a linear characteristic at about $H_y^2/H_{max}^2 = 0$. The ± sign in the above equation is determined by the inclination of the barber poles (±45°) to the strip's easy axis.

نمونه تجاری مقاومت مغناطیسی نوع AMR:

HMC1001—One Axis MR Microcircuit



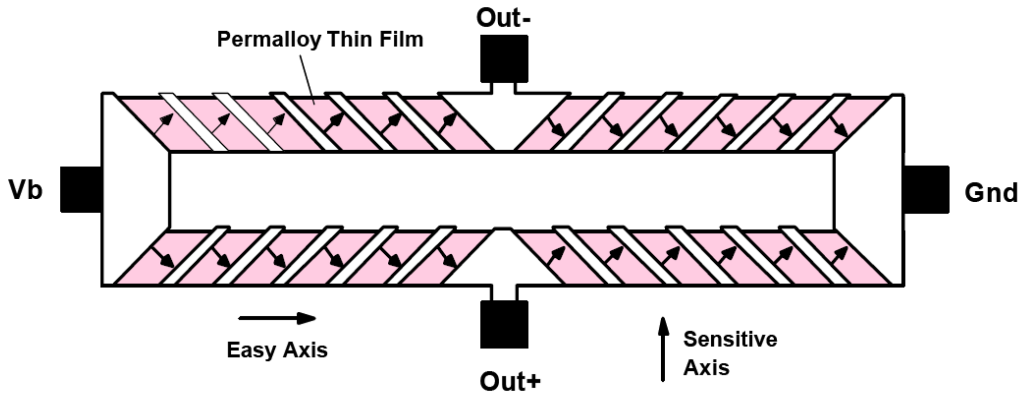
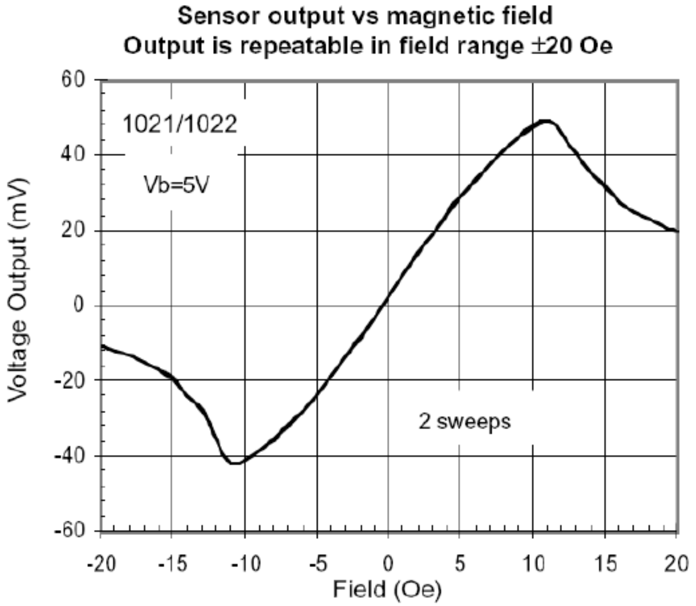


Figure 1 – Magneto-Resistive Wheatstone Bridge Elements



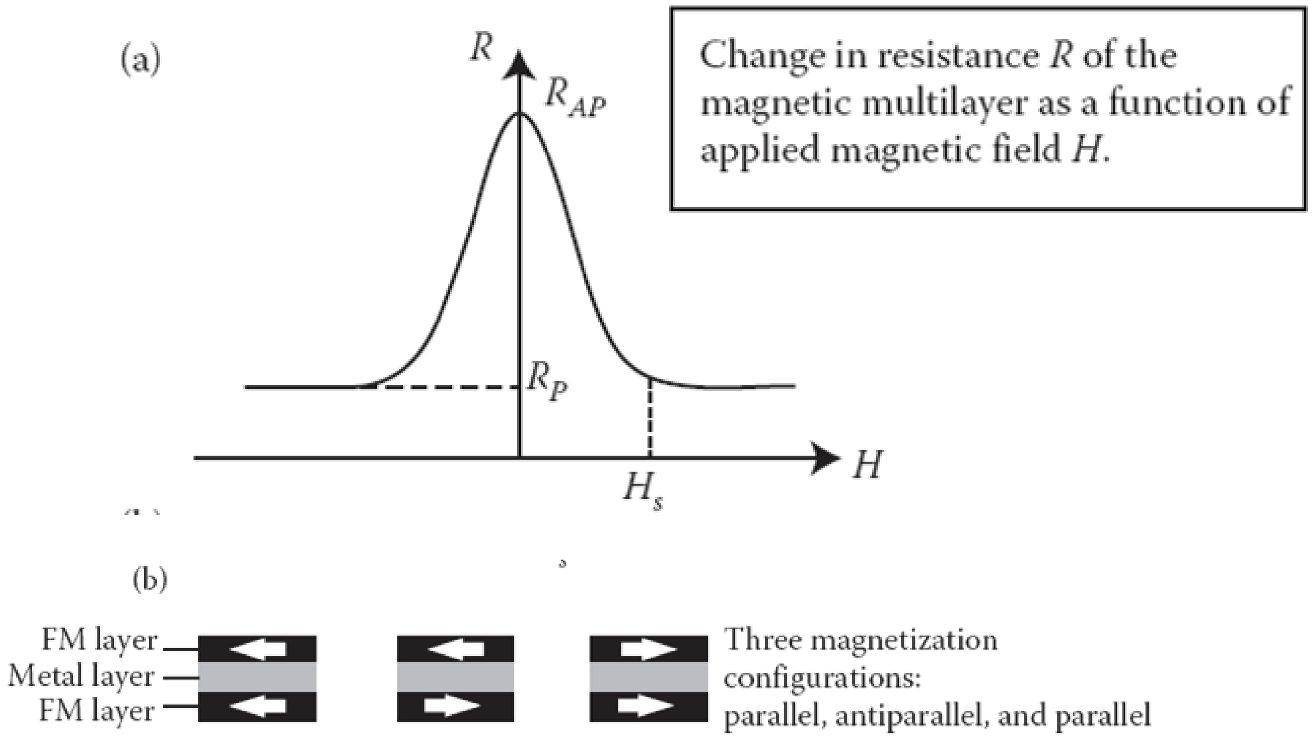
(Permalloy: Composed of a nickel–iron)

حسگر مقاومت مغناطیسی نوع GMR:

The discovery of *giant magnetoresistance* (GMR) by Albert Fert and Peter Grünberg in 1988 raised MR sensors' maximum *MR* value from 2–5% to 10% or more [4,5], a feat honored by the 2007 Nobel Prize in Physics.

Baibich et al. [9] and Binasch et al. [10] are the first who reported "Giant" magnetoresistance measured on Fe/Cr/Fe thin multilayers. They demonstrated that the electric current was strongly influenced by the relative orientation of the magnetizations of the magnetic layers. The cause of this giant change in resistance is attributed to the scattering of the electrons at the layers' interfaces. Today above 200% of *MR* value can be achieved at room temperature, which is much higher than the *MR* value of either OMR or AMR effect.

حسگر مقاومت مغناطیسی نوع GMR:



$$M_R \text{ (for GMR)} = \frac{R_{AP} - R_P}{R_P} \times 100\%$$

R_P and R_{AP} are the resistance in the parallel and antiparallel configuration, respectively.

مقایسه حسگرهای مقاومت مغناطیسی OMR، AMR و GMR:

Comparison of MR Effects

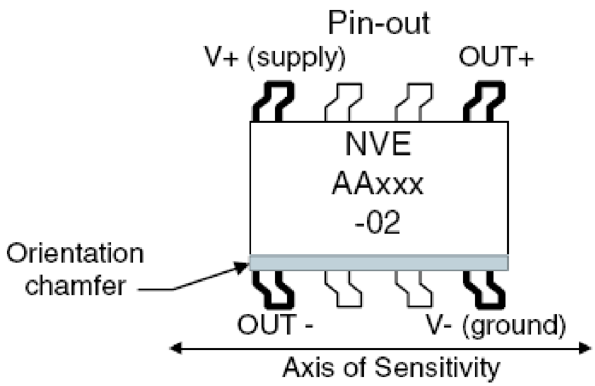
MR Effect	$\Delta R/R$ (%)	B (T)	Mechanism	Comments
OMR	<1	1 T (metal)	Lorentz force	There is no saturation at large magnetic field.
AMR	1–5	0.5 mT–1 T (depend on bulk or wire permalloy)	Electron spin–orbit interaction (leads to scattering of conducting electrons).	R is directly related to the orientation of magnetization M relative to current I.
GMR	10–200	1–10 T	Spin-dependent electron transport. In FM-metal-FM alternating layer structure.	Interface quality is crucial. They are broadly applied in sensors and read-heads of magnetic hard disks.

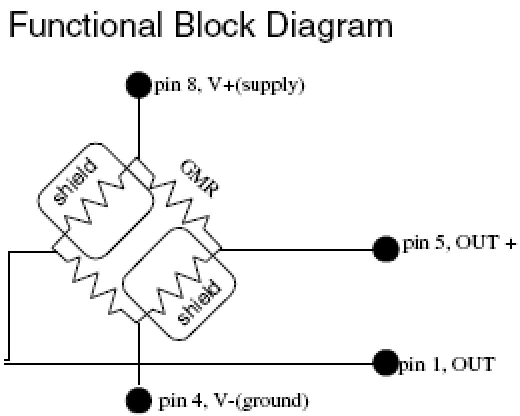
W. Y. Du "*Resistive, capacitive, inductive, and magnetic sensor technologies*", CRC Press, 2014.

نمونه تجاری مقاومت مغناطیسی GMR:

NVE AAxxx-02 GMR Sensor

NVE's Giant Magnetoresistive Field Sensors offer unique and unparalleled magnetic sensing capabilities. The high sensitivity and ability to sense static magnetic fields provides superior performance which set them apart from other sensors on the market today. NVE's sensors provide high sensitivity, temperature stability, low power consumption, and small size.





NVE's Sensors can be applied to :

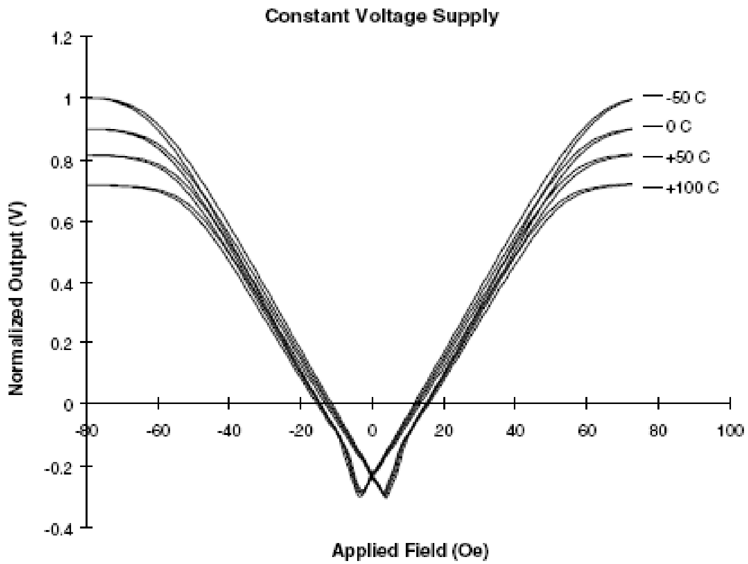
- **Proximity Sensing**
- **Motion, Speed, and Position Sensing**
- **Current Detection**
- **Magnetic Media Detection**
- **Synchronization**
- **Earth's Field Sensing**

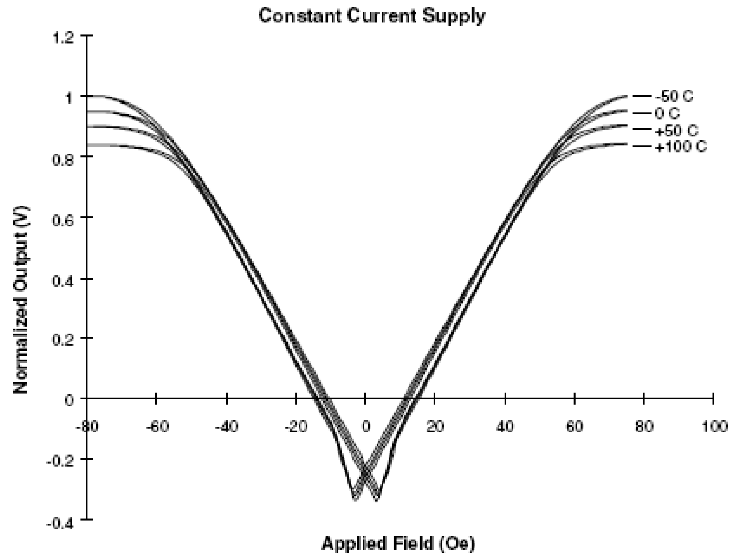
نمونه تجاری مقاومت مغناطیسی GMR:

NVE AAxxx-02 GMR Sensor

Magnetic Characteristics (5 kΩ ± 20% bridge)

Part Number	Saturation Field (Oe)	Specified Linear Range (|Oe|)		Sensitivity (mV/V/Oe)	
		Min	Max	min	max
AA002-02	15	0	10.5	3	4.2
AA003-02	20	0	14	2	3.2
AA004-02	50	0	35	0.9	1.3
AA005-02	100	0	70	0.45	0.65





نمونه تجاری مقاومت مغناطیسی GMR:

NVE AAxxx-02 GMR Sensor

General Characteristics Magnetic Field Sensors

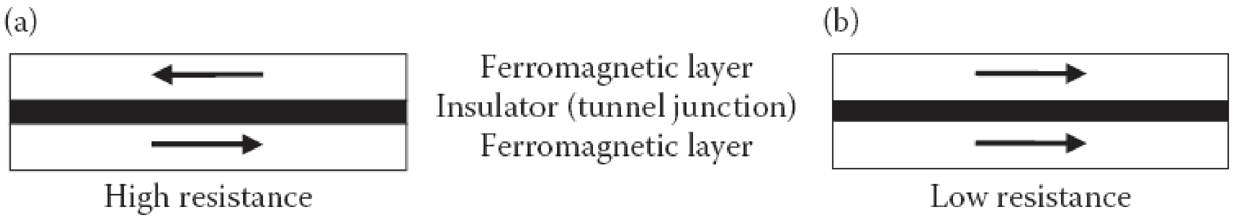
Property	Min	Nominal	Max	Unit
Input Voltage Range			±25 [4]	V
Operating Frequency	DC		>1 [5]	MHz
Temperature Range	-50		125 [4]	°C
Electrical Offset (V)	-4		4	mV/V
Max Output		45 [1]		mV/V
Nonlinearity			2 [6]	% (unipolar)
Hysteresis			4 [6]	% (unipolar)
TCR		+0.14		% / K
TCOI		+0.03		% / K
TCOV		-0.1		% / K
Off-axis Characteristic		Cos. ß [7]		
ESD		400		V pin to pin HBM

https://www.nve.com/Downloads/analog_catalog.pdf

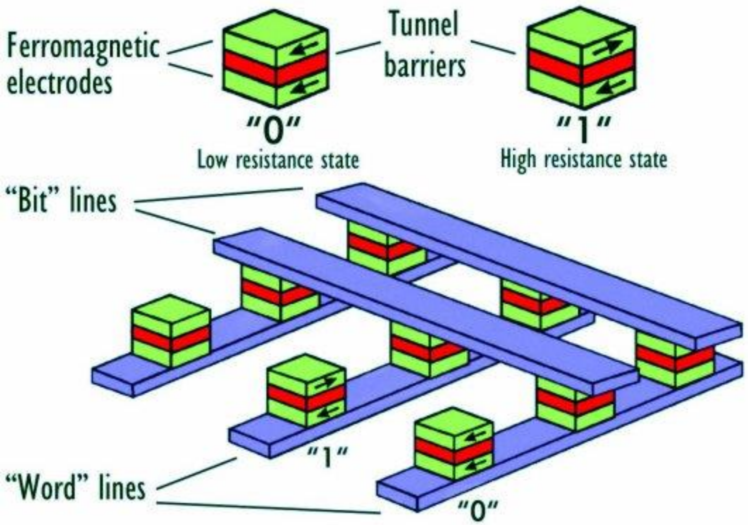
مقاومت مغناطیسی نوع TMR:

Tunneling Magnetoresistance (TMR) Effect:

IF non-FM layer in a GMR sensor is replaced by a thin insulating layer (usually aluminum oxide), the TMR effect can be observed. This insulating layer is so thin that electrons can “tunnel through” the barrier if a bias voltage is applied between the two metal electrodes.



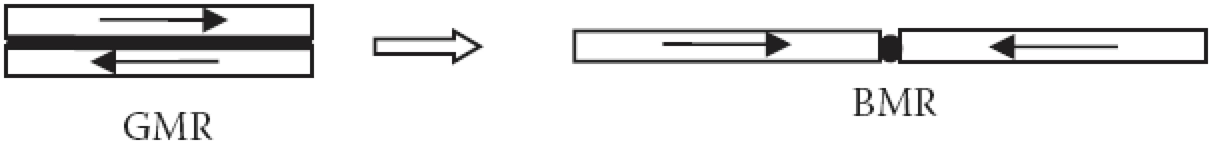
TMR, has been applied in magnetic random access memory (MRAM).



https://www.ece.nus.edu.sg/isml/research.htm

مقاومت مغناطیسی نوع BMR:

Ballistic Magnetoresistance (BMR) Effect:
In a GMR device, if the non-FM layer shrinks to a point (atomic scale), the “ballistic” magnetoresistance (BMR) effect occurs, resulting in a very large MR effect (over 3000% of *MR* value can be achieved at low magnetic fields such as a few hundred Oersteds. BMR is still in the experimental phase before its practical applications. The barrierto bring BMR to its practical applications includes the challenge to create nano- oratomic-scale point contacts between FM electrodes.



مقاومت مغناطیسی نوع CMR:

Colossal Magnetoresistance (CMR) Effect

The *Colossal Magnetoresistance* (CMR) effect, discovered in 1993, is an MR phenomenon that has *Perovskite structures*—$A_{1-x}B_xMnO_3$, where A = (La, Pr, Nd, or Sm); B = (Ca, Sr, or Ba) [16]. The term "colossal" came from the *huge* MR effects observed (~100,000%) when the resistivity of the material undergoes a *phase transition* at a low temperature from an insulating (high resistivity) phase to a metallic (low resistivity) phase. Research has shown that the CMR effect can be raised up to room temperature. *Hewlett Packard* company has produced high-quality CMR films in room temperature with a resistance change of about 95%. The major challenge associated with CMR sensors is to achieve useful, reproducible behavior at room temperature.

مقایسه حسگرهای مقاومت مغناطیسی TMR، BMR و CMR:

Comparison of MR Effects

MR Effect	$\Delta R/R$ (%)	B (T)	Mechanism	Comments
TMR	≈ 100	≈ 4 T	Spin-polarized tunneling. In FM-insulator-FM alternating layer structure.	Interface quality is crucial. They are temperature independent and applied in magnetic random access memory (MRAM).
BMR	>3000	<0.1 T	Spin scattering across very narrow magnetic domain walls trapped at nano-sized constrictions.	BMR has nano- or atomic-scale point contacts between FM electrodes. They are still in experimental phase.
CMR	≈ 100000	≈ 3 T	Insulation to conduction (metal) phase transition at Curie temperature.	CMR is extremely temperature and doping dependent. It is challenging to get useful, reproducible behavior at room temperature. They are still in study.

W. Y. Du "*Resistive, capacitive, inductive, and magnetic sensor technologies*", CRC Press, 2014.