Chapter 6

Giant Magnetoresistance Sensors Based on Ferrite Material and Its Applications

Mitra Djamal and Ramli Ramli

Additional information is available at the end of the chapter

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Abstract

In recent decades, new magnetic sensors based on giant magnetoresistance (GMR) have been studied and developed intensively. GMR materials have great potential for next-generation magnetic field sensing devices. The GMR material has many attractive features, for example, its electric and magnetic properties can be varied in a very wide range, low power consumption, and small size. Therefore, GMR material has been developed into various applications of sensor based on magnetic field sensings, such as magnetic field sensor, a current sensor, linear and rotary position sensor, data storage, head recording, nonvolatile magnetic random access memory, and biosensor. In this chapter, the recent development of a GMR thin-film–based ferrite material will be reviewed. Furthermore, recent and future trend application of GMR sensor will be discussed.

Keywords: biosensor, ferrite, giant magnetoresistance, GMR sensor, magnetic sensor

1. Introduction

In recent years, many attempts were made to improve the reliability of the sensors and sensor systems and at the same time lower the cost of fabrication. This aims to make the price of the sensor become relatively cheap. The sensors and sensor systems have been developed for various applications such as in motor vehicles, housing (e.g., for security, regulation of air circulation, temperature regulation, setting humidity), delivery of food, or warehouse storage of food (e.g., temperature, humidity, gas concentration).

In general, a sensor is defined as a device that converts physical, chemical, or biological quantities into electrical quantities. The capability of a sensor or sensor system is determined by the strong interaction of the three main constituent components, such as sensor structure, manufacturing technology, and signal processing algorithms. The development of sensor technology is also influenced by the development of these three areas as shown in **Figure 1**.

IC Insights 2017 [1] has reported that all sensor categories such as pressure sensors, acceleration sensors, and magnetic sensors and most actuators have double-digit sales in 2016. The market for sensors and actuators in 2017 is predicted to increase by 7.8% and hit a record high of $12.8 billion. Sales of sensors/actuators estimated over the next 5 years will be driven by the deployment of automated control functions that are integrated with the vehicle (including autonomous driving capability), unmanned aircraft, systems of industrial and robotics, everyday electronics, and measurement unit related to Internet of Things (IoT).

The need for new sensors and electronic interfaces, particularly in portable applications, which show small dimensions and the ability to reduce both the supply voltage and power consumption, is in continuous growth. In particular, multiple sensors and electronic circuits for interfacing developed in an integrated technology can be combined into just one chip, and enabling it to produce "smart sensor."

The phenomenon of giant magnetoresistance (GMR) has been providing cutting-edge sensor technology, especially for affordable and sensitively detect and quantify of micro-particles and nano-magnetic in very weak magnetic fields. In recent decades, sensors based on GMR effect have been researched and developed intensively [3]. The discovery of GMR has opened

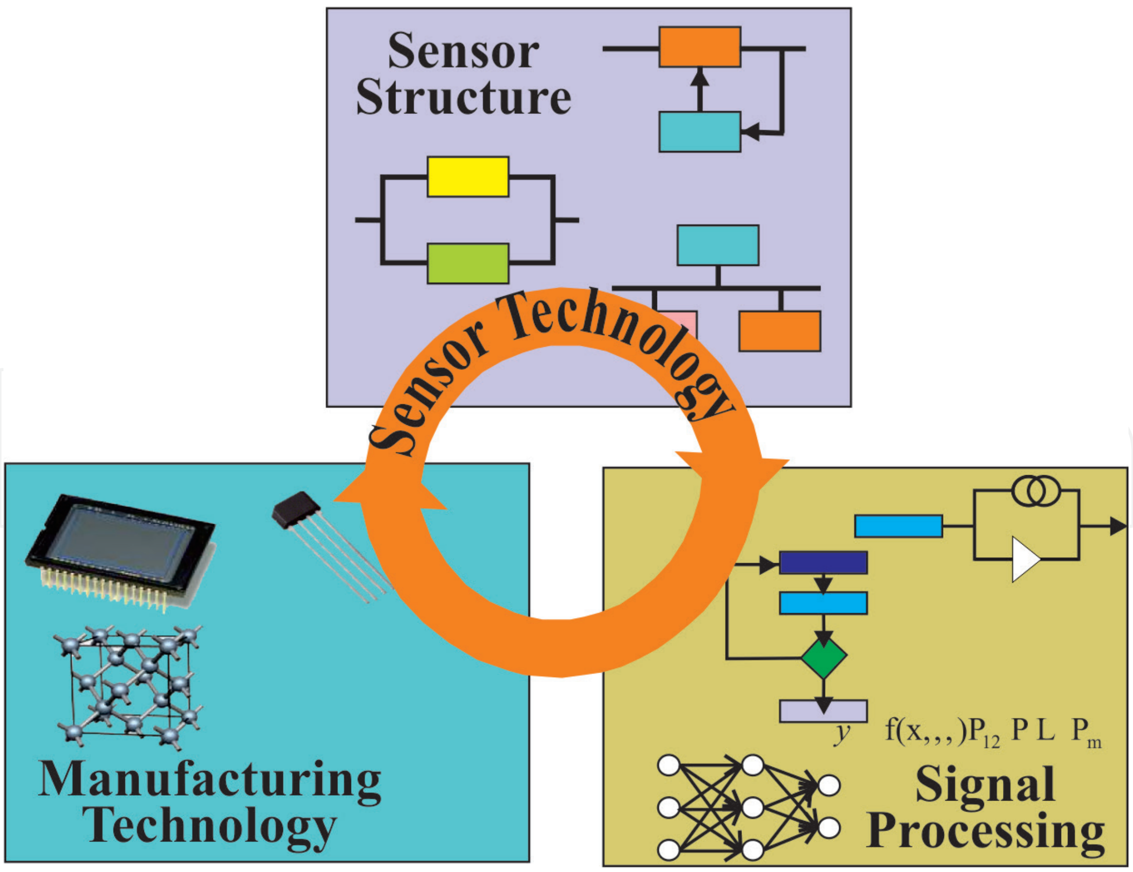

Figure 1. The three main components forming the sensor technology (adapted from Ref. [2]).

opportunities in many fields of applications. GMR material has been developed into various applications of sensor based on magnetic field sensing, such as magnetic field sensor, a current sensor, linear and rotary position sensor, data storage, head recording, and nonvolatile magnetic random access memory. The GMR material has many attractive features, for example, its electric and magnetic properties can be varied in a very wide range, low power consumption, and small size. Meanwhile, ferrite is one of the candidates of magnetic oxide material that could potentially be used as a constituent layer of GMR [4].

This chapter is organized as follows: the magnetic sensor, the GMR sensor based on ferrite material, and the GMR sensor design. Finally, the recent and the future trends of this exciting GMR sensor for various applications are discussed.

2. Magnetic sensor

Research in the magnetic sensor has been carried out by researchers in recent decades. Magnetic sensors have a significant impact over the past five decades in a variety of different fields of technology. Magnetic sensor has great potential to be developed for various applications such as magnetic storage, automotive sensors, navigation systems, nondestructive material testing, security system, structural stability, medical sensors, and military instruments [5].

Based on the measurement range of the magnetic field, approximate sensitivity ranges of different magnetic field sensors are low field (smaller than 0.1 nT), medium field (0.1–1 nT), and high field (above 1 nT), as shown in **Figure 2**.

Figure 2 shows measurement range of the magnetic field of some magnetic sensors. The GMR sensor can detect magnetic fields in the range of 10–10^8 nT and has a die size close to 1 mm.

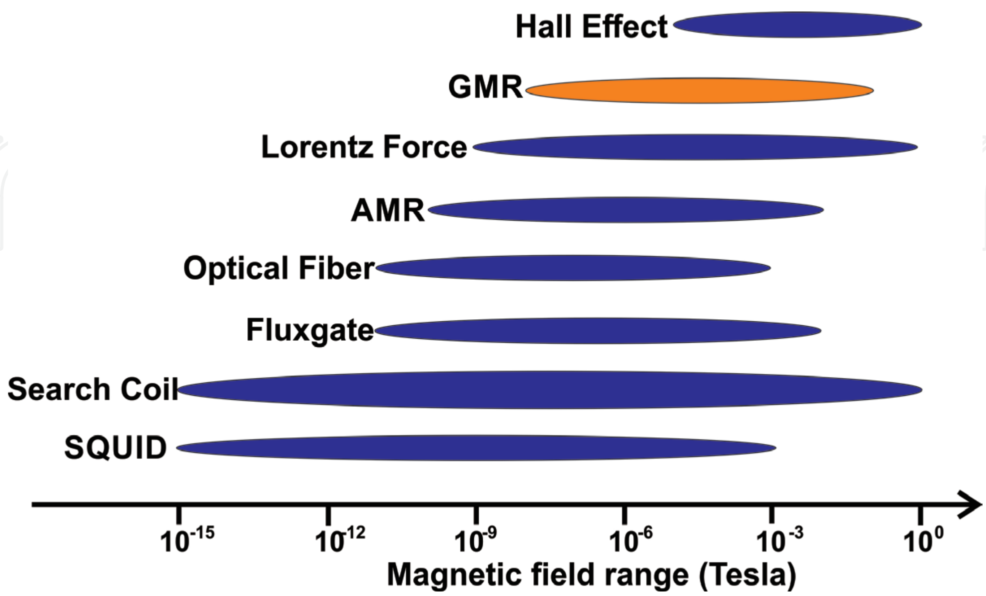

Figure 2. Approximate sensitivity range of magnetic sensor (adopted from Ref. [6]).

The dependence on temperature of the offset and sensitivity of the GMR sensor is higher than the AMR (anisotropic magnetoresistance) sensor. In addition, GMR sensors can operate at temperatures above 225°C [6].

The term "magnetic sensor" is widely used to express a sensor that works on the magnetic principles. Magnetic sensors usually work without contact with the object to be sensed and also reliable. The most important field in the application of magnetic sensors includes security, health care, information technology, geomagnetic exploration, and nanotechnology. Magnetic field sensor technology has been driven by the need to increase the sensitivity, small size, low power, low cost, and compatibility with electronic systems. To achieve these requirements, the magnetic sensors are usually created by micrometer sized or sub-micrometer with a multilayer structure.

The resistance of the material depends on the state of magnetization, called the magnetoresistance effect. Magnetization in the material can be changed by applying an external magnetic field. Therefore, the material which has a magnetoresistance effect can be used as magnetic field sensor.

The basic effect of normal magnetoresistance emerged from the Lorentz force on the electrons due to the presence of a magnetic field applied to it. Normal magnetoresistance occurs in all metals, including nonmagnetic metals as a consequence of Lorentz forces. For example, in metal thick film, cobalt (Co) with a thickness of 100 nm was observed to be positive and varies with B^2 above magnetoresistance saturation, where B is applied in a magnetic field. However, Co thin films with a thickness of 3 nm show negative normal magnetoresistance over saturated magnetoresistance. Normal magnetoresistance emerged from semiclassical arguments via the Lorentz force on electrons that are defined as

$$\vec{F} = m\left(d\vec{v}/\mathrm{dt}\right) = e\vec{E} + \left(e\vec{v} \times \vec{B}\right) \tag{1}$$

and the current density

$$\vec{j} = \left(n e^2 \tau/m\right)\vec{E} + \left(e^2 \tau/m\right)\vec{v} \times \vec{B} \tag{2}$$

where $\vec{F}$ = Lorentz force, $\vec{v}$ = electron velocity, $\vec{j}$ = current density, m = electron mass, e = electron charge, $\vec{E}$ = electric field, $\vec{B}$ = magnetic field, n = electron concentration, and τ = relaxation time.

The components of the electric field along the direction of $\vec{j}$ do not change without the presence of the magnetic field $\vec{B}$, so magnetoresistance is normally equal to zero. The presence of a magnetic field will produce a Hall field that is perpendicular to the $\vec{j}$ direction so that the Lorentz force acting on the charge carrier will increase the resistance in a magnetic field. Using the model of free electrons and then normal magnetoresistance is obtained as $(\Delta\rho/\rho) = (R_H/\rho)^2 B^2$, where R_H is the Hall resistance.

Electronic devices in the future will turn on a new field called spintronics. Spintronics is a new field that explores the influence of spin on electronic transport in magnetic nanostructures.

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Spintronic births are marked by the discovery of giant magnetoresistance effects (GMR) on magnetic multilayer Fe/Cr more than two decades ago. Accordingly, spintronics is a technology that exploits the quantum property of electrons called spin. Ordinarily, electron spins have both "up" and "down" directions and can be described as clockwise or counterclockwise around their axes. The spin gives magnetic properties on electrons that can be affected by external magnetic fields. More recently, research on spintronic devices developed very rapidly [7–9].

3. The GMR sensor based on ferrite material

The GMR-based magnetic sensor is a sensor that works based on effect of a very large change in the resistance of metal or device when an external magnetic field is applied. The magnetoresistance (MR) ratio value is written in Eq. (3):

$$\mathrm{MR} = \frac{\Delta R}{R} = \frac{R(H) - R(H=0)}{R(H=0)} \tag{3}$$

where $R(H)$ is the resistance when the device is influenced by an external magnetic field, $R(H = 0)$ is the resistance of the device without the applied external magnetic field, and H is the magnetic field intensity.

GMR material could have several structures where each structure will produce different GMR ratios. This structure consists of a sandwich, spin valve (pinned sandwich), multilayer, and granular (**Figure 3**). The sandwich structure is also called pseudo spin valve, which consists of three layers with the arrangement of materials (ferrimagnetic or ferromagnetic)/nonmagnetic/(ferrimagnetic or ferromagnetic). Accordingly, in spin valves, an additional antiferromagnetic (pinning) layer is added to the top or bottom part of the sandwich structure. Meanwhile, a multilayer structure is a structure with repetition of the sandwich layer. Similarly, the granular structure consists of granules of magnetic materials of nanometer scale scattered in nonmagnetic material as the host material.

The benefit of the GMR phenomenon is on the development of nanometer-sized technologies and possibly in the atomic scale of magnetic structures. This very thin structure has physical, chemistry, and biology properties which change dramatically, therefore, superior when compared to the bulk materials. A very thin layer can be made as an epitaxial layer (where the layer has a certain crystal arrangement with excellent monocrystalline quality) by molecular beam epitaxy (MBE) method or polycrystalline film by sputtering method [10].

Meanwhile, measurement of GMR effects has two main geometries, i.e., current In plane (CIP) and current perpendicular to plane (CPP). These two geometric shapes are shown in **Figure 4**.

Until now, researchers have continued to conduct research on GMR thin film, regarding on growth methods, constituent materials, as well as the GMR structure. Particularly for GMR constituents, ferrite is a transition metal oxide and one of the potential candidates used as the constituent material of the GMR thin film [11, 12]. Transition metal oxides are an important functional material for new electronic devices due to their unique properties such as perfect

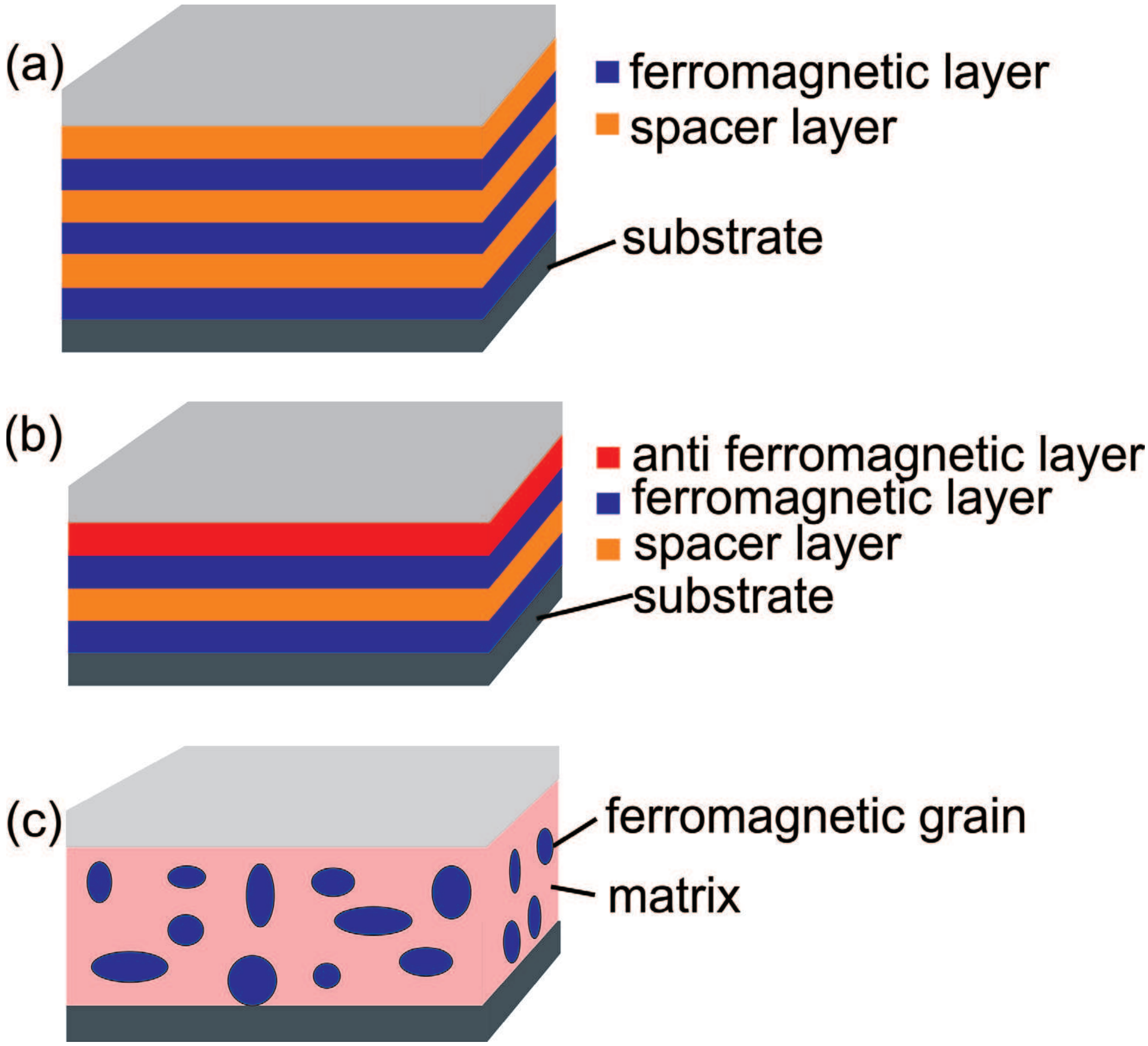

Figure 3. Various types of GMR structures: (a) multilayer, (b) spin valve, and (c) granular films.

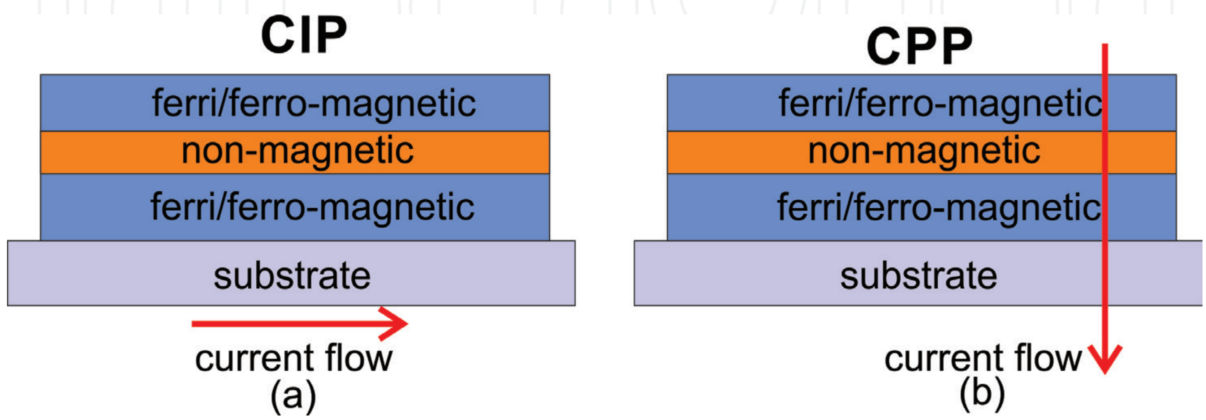

Figure 4. Geometry of GMR measurement (a) CIP and (b) CPP.

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spin polarization, large metal insulator transitions, ferroelectric, multiferroic and resistive switching effects [13]. In addition, ferrite has ferrimagnetic properties and Curie temperature above room temperature. For temperatures below the Curie temperature, ferrimagnetic materials exhibit the same behavior as ferromagnetic materials. The behavior is having a spontaneous magnetization at room temperature, consisting of saturated magnetic domains, and shows hysteresis phenomena [14]. Among the ferrite materials that have been used as GMR constituent layers are Fe_3O_4 and $CoFe_2O_4$.

The phenomenon of magnetoresistance has been observed among others the nanowires Fe_3O_4 single crystal [15], Fe_3O_4 thin film [16, 17], $Fe_3O_4/GaAs/Fe_3O_4$ junction [18], and Fe_3O_4 nanoparticles [19]. Recently, we report the results of studies relating to the synthesis of a novel ternary $CoFe_2O_4/CuO/CoFe_2O_4$ thin film as a GMR sensor [20]. The $CoFe_2O_4/CuO/CoFe_2O_4$ thin film has been prepared onto silicon substrate via dc magnetron sputtering technique with targets facing each other. The GMR ratio maximum at room temperature obtained has reached 70% for the thickness of each layer of $CoFe_2O_4$ and CuO, which are 62.5 nm and 14.4 nm, respectively. These findings provide the impact on GMR sensor technology based on ferrite material.

4. The GMR sensor design

The performance of the GMR sensor is influenced by various parameters. Among them is the composition of GMR constituent material, layer thickness, and GMR structure. The GMR structure is concerned with applications on applied technology. For example, the condition of the technology affects the performance of the spin-valve structure, so it is quite a concern because this structure is a very promising candidate for sensors and reading heads.

The following features are used to determine a good quality GMR sensor, that is [21], a large magnetoresistance ratio, large sensitivity, narrow hysteresis characterized by a low coercive field (Hc), low anisotropy field (Hk) (Hk influences sensitivity), large exchange bias field (Hex), minor changes of parameters with temperature, and have great reliability and repeatability.

The advantages of GMR sensor have a larger output than AMR sensor or Hall effect sensor and can be operated on the field above the AMR sensor field range. Some advantages of the GMR sensor compared with the AMR sensor or Hall effect sensor are listed in **Table 1**.

Advantages	GMR	AMR	Hall
Physical size	Small	Large	Small
Signal level	Large	Medium	Small
Sensitivity	High	High	Low
Temperature stability	High	Medium	Low
Power consumption	Low	High	Low
Cost	Low	High	Low

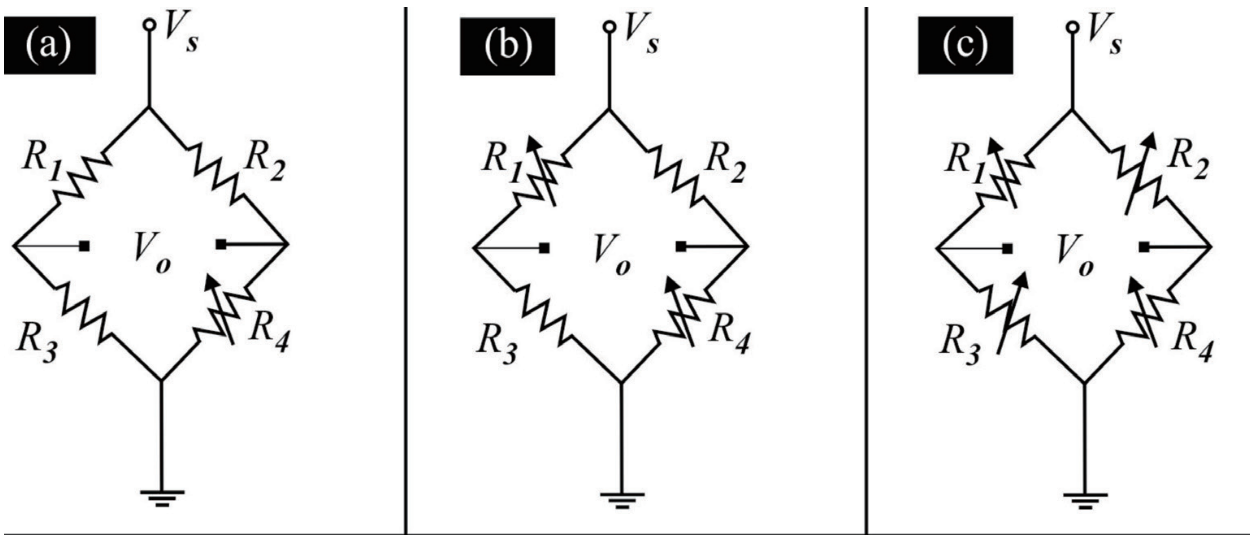
Table 1. Benefits of magnetic sensors [22].

The design and development of GMR sensors are based on assessments derived from the various areas to obtain functional devices. In addition, the special design will always be associated with specific applications. The sensor design will have an impact on the device performance. For example, both linear and thermal sensor characteristics affect the characteristics of the sensing structure and the final encapsulation. A more detailed knowledge of the sensor parameters is necessary before embarking on the development of sensors.

As a sensing element, the Wheatstone bridge circuit has been highly recommended in the design of resistive sensors. In this case, the Wheatstone bridge circuit provides a differential output as a function of the resistance variation. Depending on cases deemed or specific requirements, we can use multiple bridge configuration.

The GMR sensor made using the Wheatstone bridge principle aims to reduce the effect of hysteresis and to improve the output linearity. Ordinarily, the GMR sensor structure consists of four resistors. Two resistors are protected from exposure to the magnetic field, and two other active resistors are between two flux concentrators. The sensitivity of the GMR sensor can be changed by changing the length and distance between two flux concentrators.

Figure 5 displays a summary of the possibility of the Wheatstone bridge configuration that has been furnished by calculating the output voltage. As shown in **Figure 5**, a full bridge configuration is the best choice in terms of the signal level and linearity (**Figure 5**, right). Due to the stage dependence on the fabrication process of GMR structure, a half bridge configuration with two active resistors and two shielded resistors is often obtained when using a single-stage deposition. However, full bridge configuration is obtained if using two-step deposition.



(a) $R_1 = R_2 = R_3 = R$, $R_4 = R + \Delta R$

$$V_o = V_s \frac{\Delta R/R}{2(2+\Delta R/R)}$$

(b) $R_2 = R_3 = R$, $R_1 = R_4 = R + \Delta R$

$$V_o = V_s \frac{\Delta R/R}{2+\Delta R/R}$$

(c) $R_1 = R_4 = R + \Delta R$, $R_2 = R_3 = R - \Delta R$

$$V_o = V_s (\Delta R/R)$$

Figure 5. Wheatstone bridge configuration (a) special elements, (b) half bridge, (c) full bridge [23].

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In the design of GMR thin-film structures, it is useful to operate at the resistivity determined for the condition $w = L$ (w and L are width and length of GMR thin film, respectively):

$$R_{sq} = \frac{\rho}{t} \tag{4}$$

where R_{sq} = resistance "ohms per square," ρ = resistivity, and t = thickness of the film. One important factor in GMR sensor application is the resolution associated with the ratio of signals to noise. According to Ref. [24], the signal-to-noise ratio (SNR) is estimated to be proportional to the square root of the device area, following Eq. (5):

$$\text{SNR} = c\sqrt{\text{Lw}} \tag{5}$$

where c is a constant.

Nordling et al. [25] have used the Wheatstone bridge to develop integrated GMR sensors. This system consists of four GMRs that are integrated into serpentine, as shown in **Figure 6**. Two GMRs are formed interlocked as folded fingers act as sensing resistors (R_{S1} and R_{S2}), whereas two GMRs are spatially separated as reference resistors (R_{R1} and R_{R2}). The width of each strip is 2 μm, the separation distance is 2 μm, and the total length is more than 11 mm. Accordingly, the edges of the sensing and reference GMRs are separated by 30 μm to each other, to isolate the inbred magnetic field of each resistor, which is a function of current from leads. Hereafter, the GMR sensing elements are coated with a silicon nitride thin film to form an active surface and protect it from being in contact with the sample.

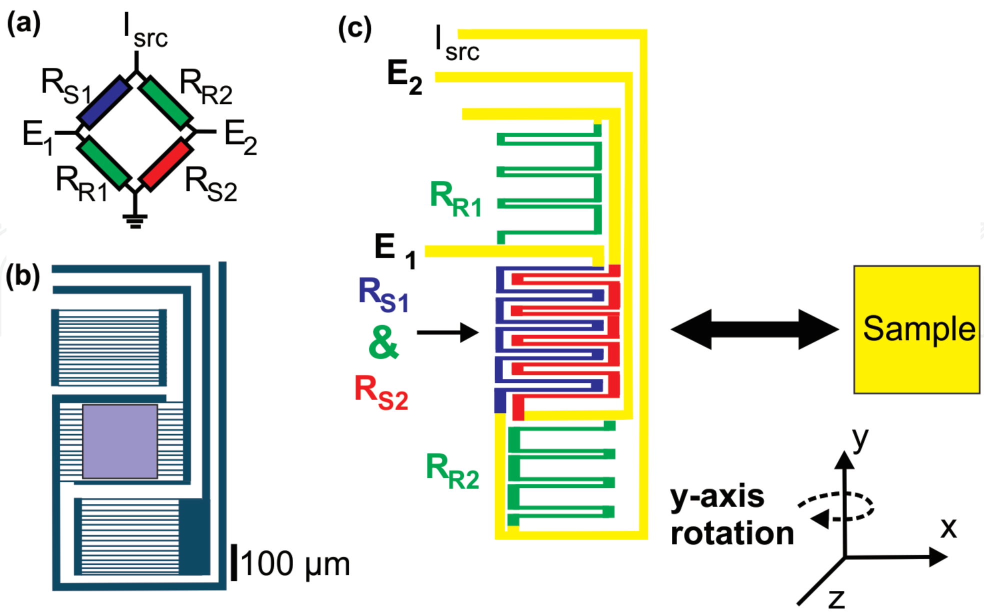

Figure 6. (a) Wheatstone bridge circuit. (b) A micrograph image of GMR sensing showing the reference GMR traces (top and bottom) and the GMR sense pad (center). (c) The schematic of the Wheatstone bridge at (b) in a circuit also shows the direction of the external field and the relative motion of GMR to the sample (adapted from Ref. [25]).

This type of resistive sensor interface of the Wheatstone bridge shows a low sensitivity value and cannot be recovered. This weakness can be corrected by using a differential input OpAmp-based voltage amplifier, to increase the sensitivity as shown in **Figure 7**.

Furthermore, the Wheatstone bridge configuration can be made "automatic" (so the circuit does not require initial calibration) through the development of a topology as shown in **Figure 8**. This circuit using a tunable resistor implemented through a voltage-controlled resistance based on the use of an analog quadrant multiplier. The variations follow those of the resistive sensor and a suitable feedback loop.

More specifically, the circuit in **Figure 8** represents a suitable configuration for ground resistive sensors placed in the lower positions of the left branch of the bridge. The output of the differential bridge is connected to an OpAmp-based differential amplifier with a voltage gain of A. Consequently, the single-ended output is sent to a voltage-inverting integrator whose goal is to create a stable negative feedback loop and provide a correct control voltage value (V_{CTRL}) for tunable resistors (R_{VCR}). If the measuring variation occurs to a specified range, the unbalanced output voltage is amplified, and the integrator produces a path that tracks the R_{VCR} elements until a new equilibrium condition is reached (i.e., automatic range).

Several studies have been conducted by researchers to improve the measurement accuracy of GMR sensor. Recently, Li and Dixon [27] have proposed the use of the closed-loop circuit to improve the measurement accuracy of GMR sensor. By using the biasing coil and feedback

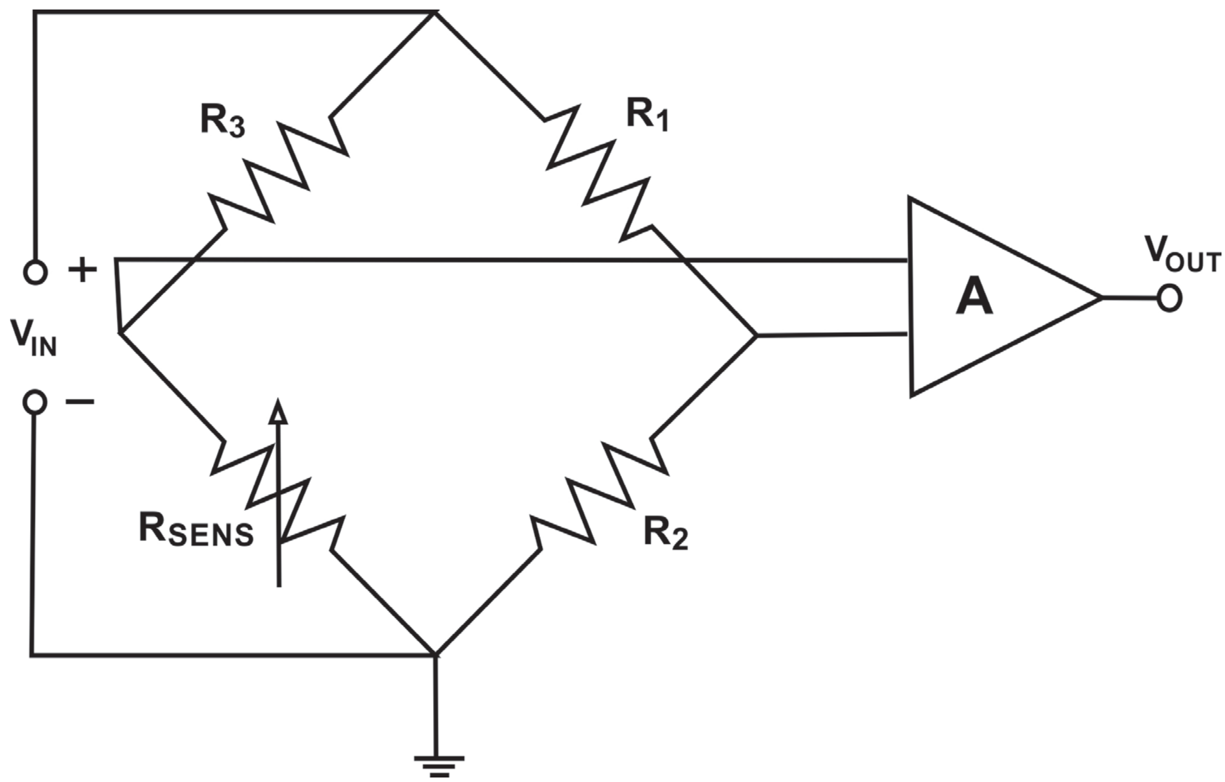

Figure 7. Differential-to-single ended Wheatstone bridge output by using a voltage differential amplifier (adopted from Ref. [26]).

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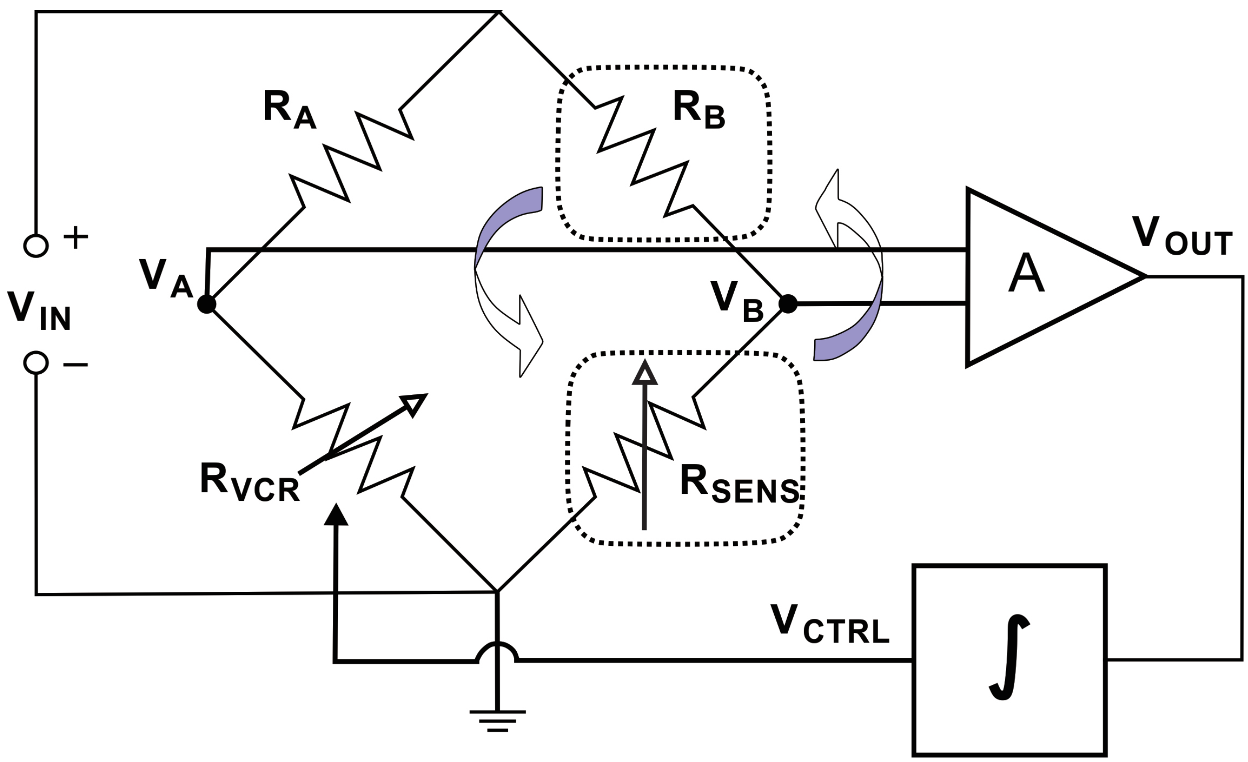

Figure 8. Block schemes of bridge-based interfaces (adopted from Ref. [26]).

circuit, the current flowing in the biasing coil is controlled by the GMR output voltage to make the GMR output constant. Hysteresis and nonlinearity of the GMR sensor have greatly minimized. Therefore, linearity and accuracy of magnetic field measurements have improved significantly.

Various efforts have been made to improve the performance of GMR sensors. An increase of 4 dB in the signal-to-noise ratio of CPP GMR sensors has been reported by Mihajlovic et al. [28]. They use Heusler alloy magnetic layers and insert an In─Zn─O electrically conductive oxide into an Ag-based metallic spacer layer.

Recently, Choi et al. [29] have shown an effective method for the enhancement of MR ratio of CPP-GMR spin-valve sensor by improving order in the B2 polycrystalline Heusler alloy films by inserting a CoFeBTa or CoBTi amorphous ferromagnetic underlayer.

5. Application of GMR sensor: recent and future trends

GMR sensors have been widely used in power systems, aerospace, modern transport systems, and the biomedical field due to the high sensitivity and wide range of magnetic field frequency response. The first application is a read head in a magnetic disk drive with the spin-valve structures. A spin-valve sensor is made of a magnetic layer exhibiting a strong coercivity (hard layer) separated by a magnetic layer with a very low coercivity (soft layer) by a thin metallic spacer.

A basic understanding of GMR device is traveling electrons from ferromagnetic layer to the other ferromagnetic layer through the conductive metal layer. If the magnetic moment in the two ferromagnetic metals is parallel then the device has a low resistance (state "0") and if the anti-parallel has high resistance (state "1"). The main attraction in the GMR technology is its ability to detect the low magnetic field. Information is stored in magnetic bits, whereas the magnetization is stored as "0" in one direction and as "1" in the other direction. This is a magnetic field detected by the GMR head. If the GMR head passes through the magnetic bits, the direction of the free layer magnetization of the head will respond with the field of each bit either spin up or down. Consequently, the magnetic moment of the free layer becomes parallel or antiparallel. This results in a change of resistance in the layers. This resistance change is detected by the GMR sensor and produces a voltage across the GMR head (while the fixed current passes through the GMR element).

The reading/writing head-integrated devices consist of a top ferromagnetic layer that is referred to as the sensing layer, and the lower ferromagnetic layer is referred to as the storage layer. The thickness of each of ferromagnetic layers is different in order to make a difference in their coercive field. The principle of reading and writing process is almost the same. However, the writing process requires a high magnetic field to rotate the moment in the storage layer.

Information is read and written by the pulse current (external magnetic field) that can detect the magnetic direction of each bit. Definition of writing is to change the magnetic moment of the storage layer (requiring high current pulses or high magnetic fields). Meanwhile, reading information on bits is changing the magnetic moment in the sensing layer (it takes a lower current pulse). The steady current passing through the GMR element is called the current sense, while the current that generates the magnetic field to rotate the magnetic moment called the word current.

The GMR sensors have been applied to measure the position of machine components as linear position detectors and transducers. A small movement of machine components (such as metal rods, gears, and other components) can produce magnetic fields. The movement along the y-axis, for example, can be determined from this magnetic field variation detected by the GMR sensor, Bx (with sensitive areas along the x-axis).

5.1. GMR sensor for detecting magnetization of liquid-contained iron

Almost all metal materials, including Fe, can be magnetized by an external magnetic field. Without an external magnetic field, the magnetic moment of the material has an irregular orientation. The magnetic moment of the material will align following the direction of the external magnetic field when the external magnetic field is applied.

The GMR sensor has been used to detect magnetic fluids containing Fe^{2+} [30] and obtain the output voltage of the GMR sensor that is proportional to the molar concentration for concentrations between 0.01 M and 0.4 M. For further experiments, it is suggested that the experiment should be conducted in a Faraday room so that the earth magnetic field cannot affect the sensor output.

More recently, GMR sensor has successfully to detect porphyrin concentration [31]. To confirm the effectiveness of this method in detecting porphyrin, we varied the flow rate and concentration of Fe^{3+}-modified porphyrin solution. **Figure 9** shows the effects of solution concentration and flow rate of the solution on the GMR output voltage. Turbidity decreases with decreasing concentration as shown in the inset image.

The result showed that the GMR sensitivity increases gradually with the increase in concentration and decrease the flow rate. Since this developed method is simple but effective for detecting porphyrin concentration, we believe that further development of this method will be a benefit for many applications, specifically relating to the medical uses.

5.2. GMR sensor for read head

Currently, we are approaching a new era of the Age of Data. Consequently, the situation changes the way we live, work, and play. That change has been initiated from the autonomous car to humanoid robots and intelligent personal assistant to the smart home devices. All of them require data storage media with very large capacity. According to a report from the International Data Corporation sponsored by Seagate, it recently states that the amount of data created worldwide will increase tenfold in 2025 [32].

In the field of digital data storage, hard disk drive (HDD) maintained its leading position among other data storage devices. In the HDD-based magnetic recording such as GMR sensors, the information is stored in the area that has been magnetized in a thin film. Transitions between similar areas are named a "bit" to be detected by a "read head" on the HDD. The number of bits per unit area is called the "areal density." Since the 1990s areal density is

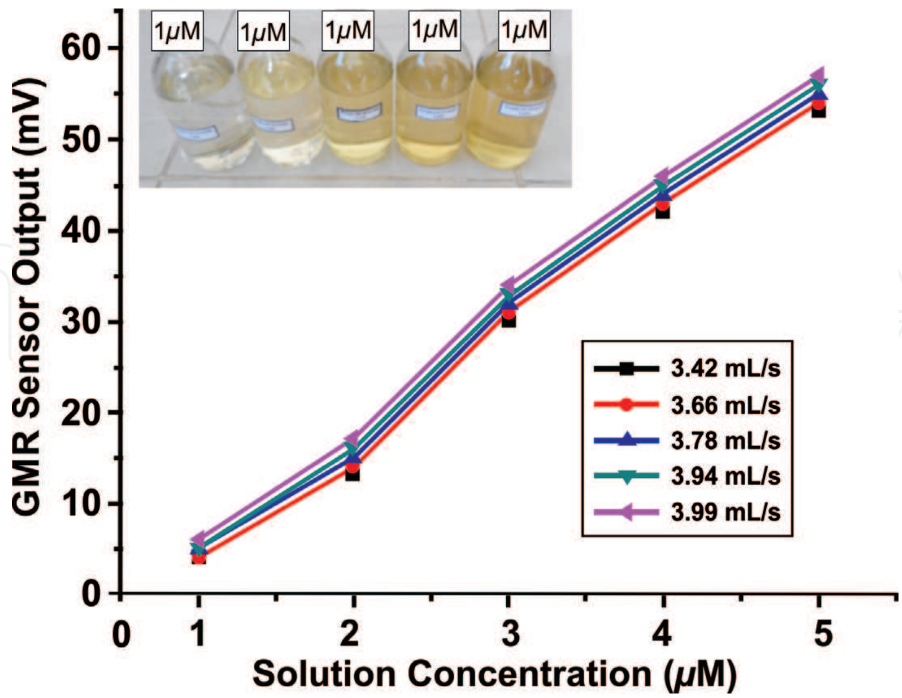

Figure 9. Effects of solution concentration and flow rate on the GMR sensor sensitivity [31].

increased dramatically, with a compound growth rate (CGR) increased to 100%, as shown in **Figure 10**. Accordingly, the need of magnetic storage media with a large capacity and small size requires a serious development of magnetic field sensors based on GMR material.

The GMR head is an analog device that detects magnetic marks with magnitude above high-resolution disks, rather than directly detecting the binary magnetization of stored bits. GMR head development trends are intended to achieve large-scale data storage densities. A simple diagram of the GMR head is shown in **Figure 11**. The sensing layer in the GMR head consists of a free and a reference layer, which is separated by a nonmagnetic layer.

Another phenomenon related to GMR is spin torque. Nowadays, a high-sensitivity spin-torque oscillator (STO) for ultrasmall field sensors has been used for storage devices. STO usually appears in one of two very different architectures: (i) nano-pillars approximately 100 nm in diameter and (ii) nano-contact, where the current enters a long magnetic structure through constriction [34].

The increase of the capacity of data storage devices raises the gap between processor speed and off-chip memory speed, resulting in increased demand for on-chip memory, more recently. The way to limit power consumption and to save memory gaps is by modifying the memory hierarchy by integrating instability at different levels, which will cause static power and also pave the way to normal-off/instant-on computation [34].

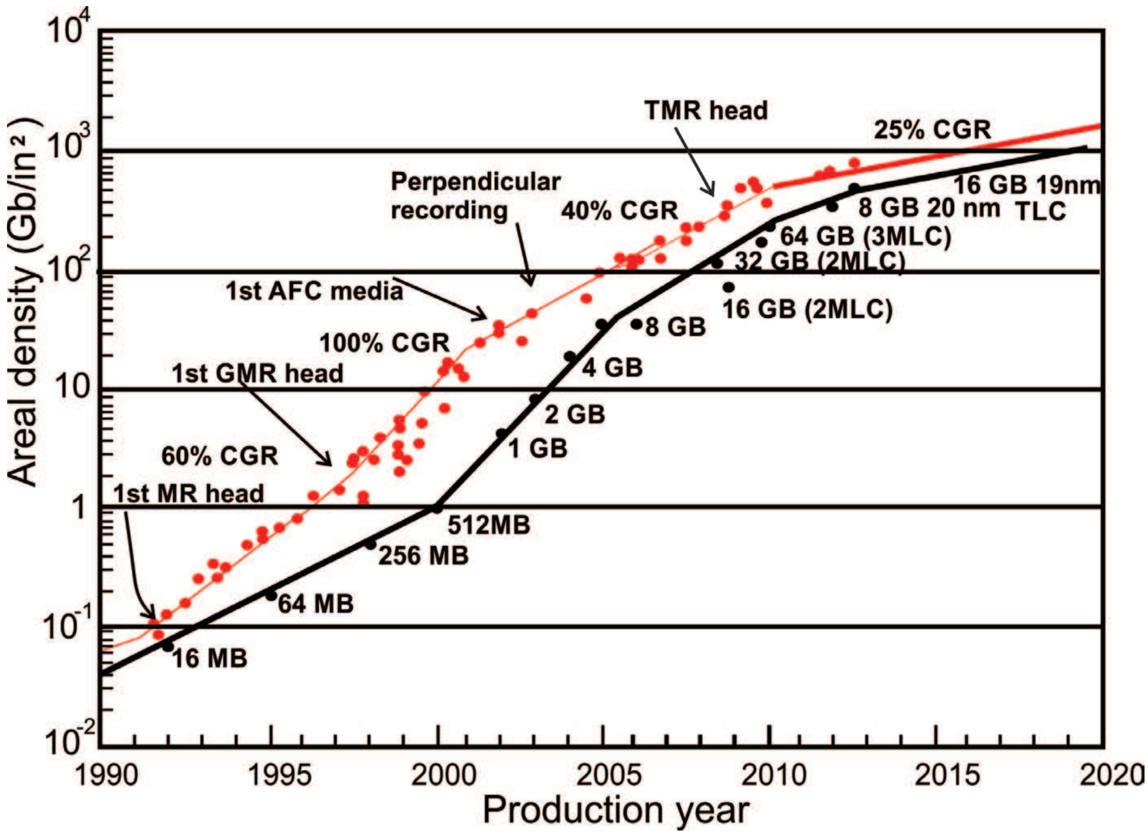

Figure 10. Trend of the increase of areal density of HDD and flash disk to the year of production [33].

5.3. GMR biosensor and biomedical application

Since the late 1990s, magnetoelectronics has emerged as one of several new platform technologies for biosensor and biochip development [36]. This technology is based on the detection of biologically functionalized micrometer- or nanometer-sized magnetic labels, using high-sensitivity microfabricated magnetic field sensors.

The development of a biosensing platform that is powerful, flexible, and high throughput is expected to have broad implications in medicine, nursing clinical diagnostics, pharmaceutical drug development, genomics, and proteomics research. It is enabled by nanotechnologies, which is emerging rapidly (i.e nanoparticles, nanotubes, and nanowires) and micro manufacturing technology (i.e MEMS- micro electro mechanical systems, microfluidics, and CMOS- complementary metal-oxide-semiconductor). Some platforms new sensing has been proposed and tested for biomedical applications, one of which is a GMR biosensor [37].

Biomolecular detection using GMR sensors is based on the principle that the resistance of the GMR sensor changed when an external magnetic field is applied. When a magnetically labeled biomolecule is brought close to the sensor, a signal will be transmitted and read by the GMR sensor. Today, GMR-based biosensors are very sensitive to detect magnetic information so that it has become a dominant player in the field of biosensors.

The use of GMR sensors for magnetic marker detection was first developed by Tondra et al. [38]. They concluded that all sizes of a single magnetic marker can be detected by the GMR sensor provided the sensor size is almost identical to the size of the marker as well as a thin isolated protective layer. Millen et al. [39] has proposed the incorporation of GMR structures on bacterial sensing as shown in **Figure 12**. Surface sensing regions of GMR need to be modified to allow for binding of antibody capture. If a sample solution containing a target antigen concerns the GMR sensor, then a complex bond exists between the target antigen and the antibody. Furthermore, it is followed by the addition of magnetic-coated antibody particles and labeled the antigen target to form a sandwich-like structure.

Currently, one of the topics of biomedical research interest is the detection of biological species. Basic research in this field will result in many immediate applications, such as food-borne

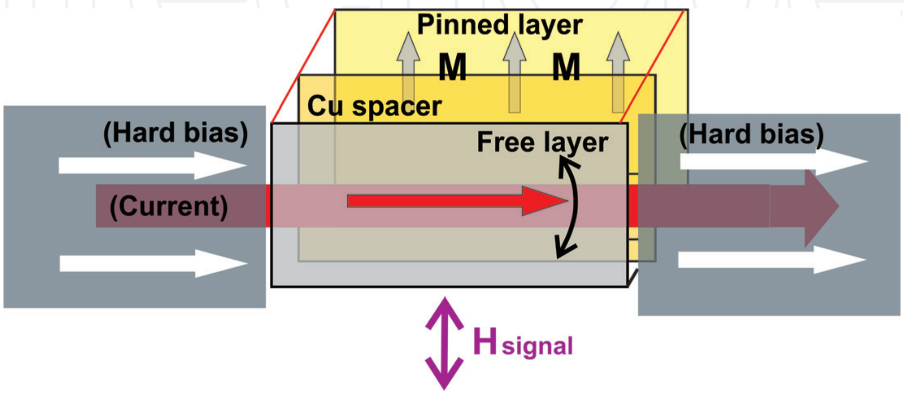

Figure 11. A simple diagram of the GMR head (adopted from Ref. [35]).

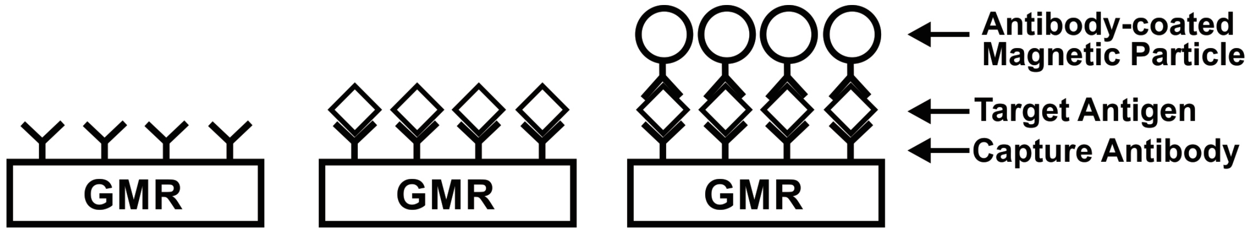

Figure 12. Bacterial detection scheme with GMR biosensor (adapted from Ref. [39]).

pathogen detection, biological war defense, or bio-diagnosis. In this scenario, it is necessary to develop an easy, inexpensive, and quick method to detect this agent. Manteca et al. [40] combined superparamagnetic particles with GMR sensors to detect target species. Recently, Elaine et al. [41] have shown examples of sensitive and specific multiplexed detection of major peanut allergens and wheat allergens gliadin using an array of GMR sensors. They found that the multiplexing capability of GMR sensor arrays provides higher levels of information that is unavailable with current commercialized enzyme-linked immunosorbent assay (ELISA) detection kits.

Krishna et al. [42] have developed a simple and sensitive method for detecting influenza A viruses using GMR biosensors. This test uses monoclonal antibodies against viral nucleoproteins (NP) in combination with magnetic nanoparticles (MNPs). The presence of influenza viruses allows the binding of MNPs to GMR sensors; consequently, their binding is proportional to viral concentrations. The binding of MNP to the GMR sensor causes a change in the sensor resistance, as measured in real-time electrical readings. Illustration of GMR biosensor for detecting influenza A virus is shown in **Figure 13**.

The GMR sensor has been used in heart rate monitoring. Kalyan et al. [43] have developed a simple cardiac rate monitoring system using GMR sensor. The GMR sensor is placed on the human wrist and provides a magneto-plethysmographic signal. This signal is processed by a simple analog and digital instrumentation stage to give an indication of heart rate. The prototype of this system is shown in **Figure 14**.

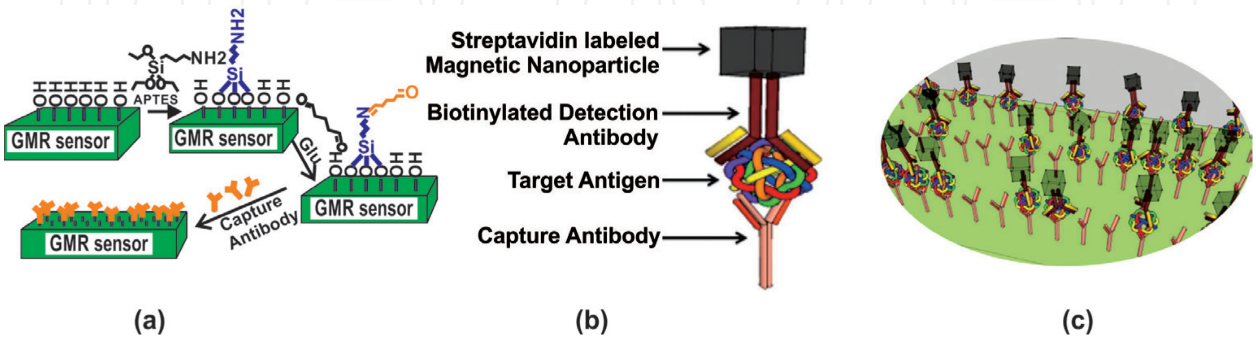

Figure 13. Schematic representation of GMR biosensor. (a) Schematic diagram of GMR biosensor surface functionalization. (b) Schematic drawing of a typical sandwich structure (biotinylated detection antibody/target antigen/capture antibody). (c) Schematic illustration of influenza A virus detection (adopted from Ref. [42]).

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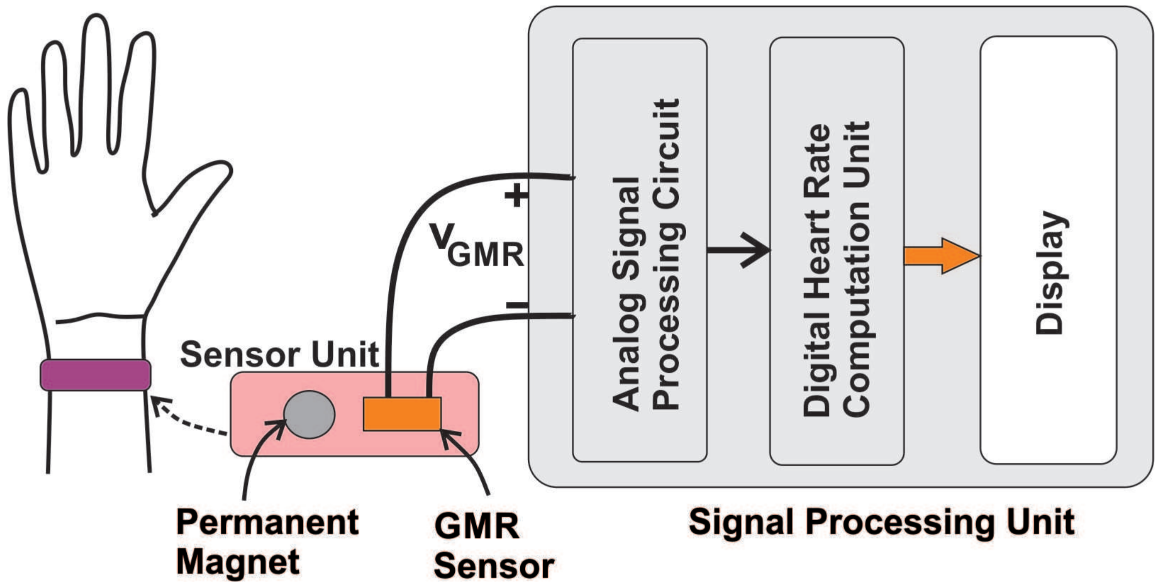

Figure 14. Simplified diagram of the proposed GMR heart rate monitor. It uses a GMR sensor and magnet in the sensor unit to get the plethysmograph (v_{GMR}) and heart rate (adopted from Ref. [43]).

5.4. GMR sensor as magnetometer

The GMR sensors have advantages of low power consumption, low cost, high detection capability, linearity, and three-dimensional (3D) measurement capabilities, thus matching the need for a magnetometer. Luong et al. [44] have proposed a three-dimensional GMR sensor design with a single bridge and one flux guide for the three-dimensional magnetometer. This design helps to reduce the sensor size, power consumption, and fabrication cost.

Recently, Xiao [45] has reported the use of GMR sensors for steering wheel angle sensors with high accuracy, wide measurement range, and simple structure. It used two GMR chips to detect magnetic fields. The GMR chip measures the rotation angle of the multipole magnetic ring with 120 couples of a magnetic pole, whereas each magnetic pole of which outputs an angle signal of 0–360.

In nondestructive test (NDT), GMR sensor as a magnetometer has implemented to detect the material defect profile. The sensing axis of the GMR sensor is set perpendicular to the direction of the excitation magnetic field; consequently, the information collected primarily reflects changes in the eddy current caused by the defect. Moreover, application of the GMR sensor as a signal receiver has increased the sensitivity of this technique in the detection of small defects [46]. The implementation of the GMR sensor on NDT eddy current techniques is still new, and many issues related to hybrid systems (coils-GMR) will continue to be explored by researchers.

Recently, Gao et al. [47] have designed a 4-GMR probe with a rectangular coil as the excitation coil and an eddy current detection system to detect weld defect (**Figure 15**). The experiments conducted by Gao et al. [47] showed that through the method of the proposed detection system, the recognition rate was 92% for flawless welding and 90% for welding with defects, with an overall recognition rate of 90.9%. This shows that the method can detect weld defects effectively.

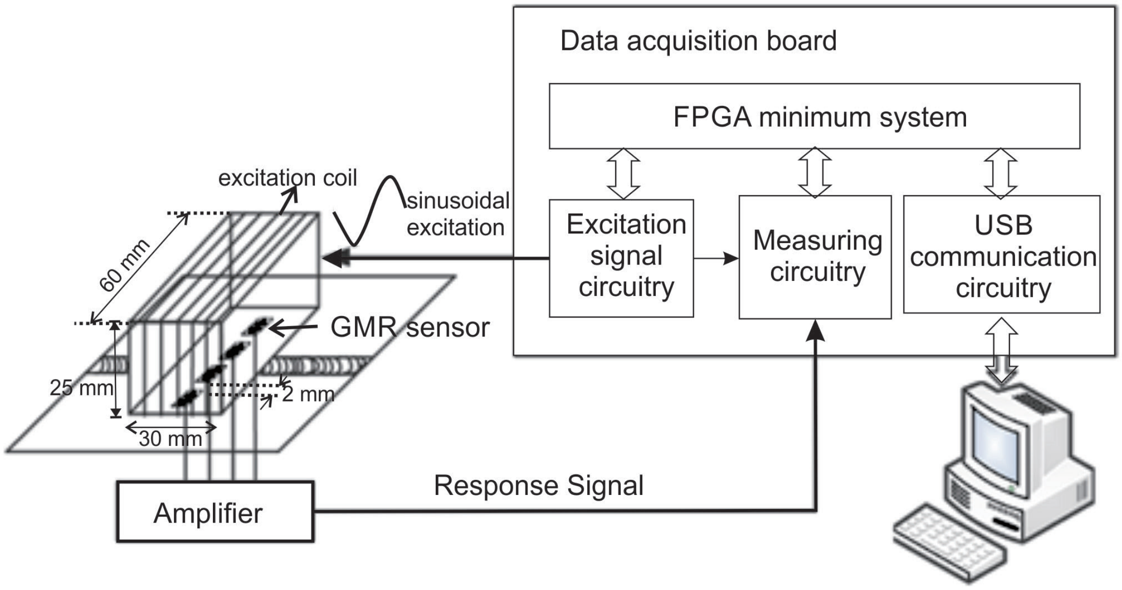

Figure 15. Schematic graph of eddy current testing system and weld inspection based on GMR sensor (adopted from Ref. [47]).

6. Conclusion

The use of GMR material for sensor applications is increasing rapidly, as a result of its small size, high signal level, high sensitivity, high-temperature stability, low power consumption, low cost, and compatibility with CMOS electronics. Some sensor applications have been developed using GMR material, e.g., magnetic sensors, read head sensors, biosensors, and many others. In the future, the development of GMR-based sensors will increase continuously, especially for health application, data storage, and daily needs.

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Author details

Mitra Djamal[1,2]* and Ramli Ramli[3]

*Address all correspondence to: mitra.djamal@yahoo.co.id

1 Department of Physics, Institut Teknologi Bandung, Bandung, Indonesia

2 Department of Physics, Institut Teknologi Sumatera, Lampung Selatan, Indonesia

3 Universitas Negeri Padang, Padang, Indonesia

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