Development of Sensors Based on Giant Magnetoresistance Material

Article *in* Procedia Engineering · December 2012
DOI: 10.1016/j.proeng.2012.01.1237

2 authors:

Mitra Djamal
Bandung Institute of Technology

Ramli Ramli
Situs Resmi Universitas Negeri Padang

Available online at www.sciencedirect.com

SciVerse ScienceDirect

Procedia Engineering 32 (2012) 60 – 68

Procedia Engineering

www.elsevier.com/locate/procedia

I-SEEC2011

Development of Sensors Based on Giant Magnetoresistance Material

Mitra Djamal[a*] and Ramli[a,b]

[a]Theorectical High Energy Physics and Instrumentation Resarch Group, Institut Teknologi Bandung, Bandung, 40132, Indonesia
[b]Department of Physics, Universitas Negeri Padang, Padang, 25131, Indonesia

Elsevier use only: Received 30 September 2011; Revised 10 November 2011; Accepted 25 November 2011.

Abstract

In this review we discuss development of sensors based on giant magnetoresistance (GMR) material.The GMR material has high magnetic and electrical properties, therefore it has great potential as next generation magnetic field sensing devices. During the last decade, intensive research efforts have been expended to develop sensors based on giant magnetoresistance (GMR) material, both based on inorganic materials and organic materials. Many application of GMR sensor, such as: current sensor, linear and rotational position sensor, head recording, and biosensor, are reviewed.

Keywords: Biosensor; Ferromagnetic; Giant Magnetoresistance; Sensor; Spintronics

1. Introduction

Magnetoresistance is the change in metal or device resistance that influenced by magnetic field. Very large magnetoresistance effect called giant magnetoresistance (GMR). GMR effect is a basic research topic during the late 1980s. GMR phenomenon sucks a lot of attention of researchers and become an extensive area of applied research. In a relatively short time, its application began to appear in the form of improved memory devices and sensors. The discovery of GMR has opened up opportunities for its application in many fields. Some devices that work on the phenomenon of GMR have been developed.

Generally, sensors for measuring the magnetic field include fluxgate sensor, Hall sensor, induction coil, GMR sensor, and SQUID sensor. Due to advantages of GMR materials for magnetic field

* Corresponding author. Tel.: +62 22 2500834; fax: +62 22 2506452.
E-mail address: mitra@fi.itb.ac.id.

1877-7058 © 2012 Published by Elsevier Ltd.
doi:10.1016/j.proeng.2012.01.1237

measurements, such as: high sensitivity and quick response under low magnetic field, more attentions have been paid on developing GMR material for magnetic field sensors. The first commercial GMR sensors were introduced in 1994 [1]. Nowaday, GMR-based sensors, both commercial and own developed, have been successfully applied in different scenarios. While almost universally employed as compact, high-density, and high speed read heads in computer hard drives [2], GMRs have also found specialty applications in several other areas [3, 4, 5] including antilock brakes [6], magnetic imaging [7], galvanic isolators [8], biosensor [9, 10] and magnetocardiography [11].

2. GMR Principle

The basic principle of the magnetoresistance (MR) is the variation of the resistance (R) of a material or a device as a function of an external magnetic field (B), as generally described by the following general equation:

$$R = f(B) \qquad (1)$$

Magnetoresistance (MR) is defined as a change in the electrical resistance of a substance in the presence of a magnetic field. The signal response of a device is often characterised by the percentage MR, as shown by equation (2), where *ΔR* is the change in resistance in an applied field and *R* is the resistance in the absence of an applied field:

$$MR(\%) = \frac{\Delta R}{R} \times 100\% \qquad (2)$$

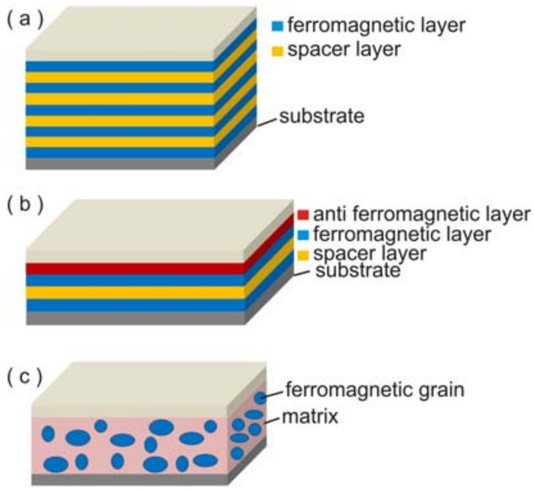

Fig. 1. Various types of GMR structures: (a) multilayer; (b) spin valve and (c) granular films

In 1988, Baibich et al. [12] and Binasch et al. [13] reported for the first time on what they called ”Giant” magnetoresistance measured on Fe/Cr thin multilayers. They demonstrated that the electric current in a magnetic multilayer consisting of a sequence of thin magnetic layers separated by equally thin non-magnetic metallic layers is strongly influenced by the relative orientation of the magnetizations of the magnetic layers (about 50% at 4.2 K). The cause of this giant variation of the resistance is attributed to the scattering of the electrons at the layers interfaces. This way, any structure with metal-magnetic interfaces is a candidate to display GMR. Since then, a huge effort has been carried out in finding structures to enhance this effect (MR levels at room temperature above 200% are achieved in modern GMR structures).

Recently, we have successfully developed GMR thin film with sandwich structure using dc-opposed target magnetron sputtering, and we obtained about 65 % MR value at room temperature in NiCoFe/Cu/NiCoFe sandwich [14, 15].

The giant magnetoresistive effect is a benefit of technological development that allows different magnetic structures to be obtained at nanometer and even atomic scales [16]. These ultrathin structures exhibit a wide range of mysterious and surprising phenomena which do not exist in bulk materials. The typical thin film nanostructures may be created as epitaxial films (films with ordered crystal structures of good monocrystalline quality) prepared by using the MBE method (molecular beam epitaxy) or polycrystalline films prepared by using the sputtering method. These films are formed as multilayers, for example a 'sandwich structure' (Fig. 1(a)) where a third, very thin nonmagnetic film (the *spacer layer*), is placed between two magnetic films. The border between the films is called the *interface*. The artificially grown structure consists of periodically alternating single-crystal film layers and is called the *superlattice*. Small magnetic entities may be introduced into the nonmagnetic matrix and this nanocomposite system is called the *granular system* (Fig. 1(c)).

2.1. Multilayer GMR Structure

A multilayered structure consist of two or more magnetic layers of a Fe–Co–Ni alloy, as can be permalloy, separated by a very thin non magnetic conductive layer, as can be Cu [17]. A general scheme is shown in Fig. 1(a). With magnetic films of about 4–6 nm width and a conductor layer of about 3–5 nm, magnetic coupling between layers is slightly small. With this configuration, MR levels of about 4%–9% are achieved, with linear ranges of about 50 Oe. The figures of merit of these devices can be improved by continuously repeating the basic structure. Successful applications of multilayered structures in magnetic field sensing include bioelectronics [18] and angle detectors [19].

2.2. Spin Valve GMR Structure

An effective method of improving of the sensitivity of GMR sensors was introduced in 1991 by Dieny and co-workers [20]. They proposed a new type of GMR sandwich structure termed a spin-valve (SV) sensor. In the spin-valve structure the antiferromagnetic alignment is obtained not by exchange coupling between two ferromagnetic films. This biased layer (called the fixed or pinned layer) is separated by a nonferromagnetic spacer from the second ferromagnetic layer (free or unpinned layer).

The origin of spin valves are a particular case of multilayered structure. In spin valves, an additional antiferromagnetic (pinning) layer is added to the top or bottom part of the structure, as shown in Figure 1(b). In this sort of structures, there is no need of an external excitation to get the antiparallel alignment. In spite of this, the pinned direction (easy axis) is usually fixed by raising the temperature above the knee temperature (at which the antiferromagnetic coupling disappears) and then cooling it within a fixing magnetic field. Obviously, so obtained devices have a temperature limitation below the knee temperature. Typical values displayed by spin valves are a MR of 4%–20% with saturation fields of 0.8–6 kA/m [21].

For linear applications, and without excitation, pinned (easy axis) and free layers are arranged in a crossed axis configuration (at 90°). The response this structure is given by [22]:

$$\Delta R = \frac{1}{2}\left(\frac{\Delta R}{R}\right) R_s \frac{iW}{h} \cos\left(\Theta_p - \Theta_f\right) \quad (3)$$

where (ΔR=R) is the maximum MR level (5%–20%), R_s is the sensor sheet resistance (15–20 Ω/m), L is the length of the element, W is its width, h is the thickness, i is the sensor current, and Θ_p and Θ_f are the angle of the magnetization angle of pinned and free layers, respectively. Assuming uniform magnetization for the free and pinned layers, for a linearized output, $\Theta_p = \pi/2$ and $\Theta_f = 0$. The term 'spin-valve' followed from the term 'magnetic valve' introduced by Slonczewski (1989) [23] for the tunnelling effect in ferromagnetic layers. Spin-valve means that the magnetizations of the layers act as a sort of valve for conduction electrons.

2.3. Granular GMR Structure

The granular GMR structure consists of nanometer-size granules of magnetic material dispersed in a nonmagnetic host material [24, 25, 26, 27]. This structure is usually prepared by codeposition of magnetic and nonmagnetic metals. Because of the immiscibility of some transition metals with noble metals it is possible to obtain a mixture of a nonmagnetic matrix with precipitated magnetic entities. It is also possible to obtain the granular structure straight away by sputtering deposition from the composite material target [28]. Directly after the sputtering process a large saturation field is necessary to exhibit the full value of magnetoresistance – about 4000 kA/m. But after annealing, when the granular structure stabilizes it is possible to obtain magnetoresistance for a saturation field smaller than 1000 A/m.

Another method of manufacturing the granular structure was proposed by Parkin and co-workers [29]. The granular structure was obtained by appropriate molecular beam epitaxial growth of Co/Cu and Co/Ag films. It was possible to prepare the granular structure by slow co-evaporation under UHV conditions and at moderate (below 400°C) substrate temperature. Even without annealing a large magnetoresistance ratio was obtained, exceeding 70% at 4.2 K for the CoAg alloy. In (111)-oriented Co-Ag film Co particles with diameter of 2.5 nm separated from each other by a distance of 8 nm were created.

Today, the new GMR materials based organic material obtained after allowing for Organic Magnetoresistance (OMAR) was found in OLEDs (organic light-emitting diodes) devices [30, 31, 32]. This organic material is used as a spacer layer in GMR devices with spin-valve structures. Traditionally, metals and semiconductors are used as a spacer layer in spin-valve. However, several factors such as spin scattering caused by large atoms of the spacer material and the interface scattering of ferromagnetic (FM) with a spacer, will limit the efficiency of spin-valve.

One proposed solution is to use organic material as a spacer. The organic materials such as polymers π - conjugated and organic semiconductors have weak spin-orbit interactions, which making possible to maintain the coherence of the spin several times longer than the metal and semiconductor. Besides that the organic material is low cost, lightweight, mechanically flexible and easy to be modified.

3. GMR Sensor

GMR sensors are rather complex systems and therefore various parameters influence their performances. The composition of the material or the thickness of the layers are specific for different GMR structures and have been analysed in previous chapters. Common to all structures are the technology dependent problems of the quality of deposited structures. The technological conditions affecting spin-valve performances as an example will be analysed in more detail because this structure is the most promising candidate for sensors or reading heads.

A good quality GMR sensor should exhibit following features [33]: large value of magnetoresistivity ratio $(\Delta R/R)_{max}$, = $(R_{max} - R_{min})/R_{max}$, large sensitivity $S = (\Delta R/R)_{max}/H_s$, small hysteresis usually described by coercive field H_c, small anisotropy field H_k of the unpinned layer (sensitivity depends on H_k), large exchange biasing field H_{ex}, small changes of parameters with temperature and good repeatability and reliability.

GMR sensors have greater output than conventional anisotropic magnetoresistive (AMR) sensors or Hall Effect sensors, and are able to operate at fields well above the range of AMR sensors. In addition, high fields will not "flip" GMR sensors or reverse their output as is possible with AMR sensors. GMR sensors have significant advantages over Hall Effect and AMR sensors as shown in Table 1.

Table 1. Benefits of Magnetic Sensors [34]

Benefits	**GMR sensor**	AMR sensor	Hall sensor
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

3.1. GMR for Current Sensor

Conventional methods of current measurements utilize the resistor shunt technique. However, this technique exhibits several serious drawbacks. The most important disadvantage is the lack of a galvanic separation between the source (very often of high voltage) and measuring equipment. Another disadvantage of the shunt is the necessity of breaking the conductor, which is not always possible, for example in printed circuit boards (PCB) or high voltage circuits. Another conventional method of current measurement is the use of measuring transformers. This method introduces additional errors (for example hysteresis) and is typically limited to large AC currents. Therefore the shunts or the measuring transformers are often substituted by Hall-sensor current transducers.

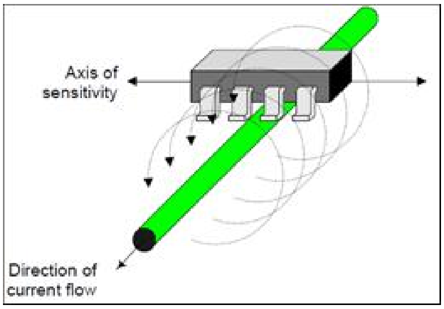

Fig. 4. GMR sensor package orientation for detecting the field from a current-carrying wire [35]

Due to better sensitivity, linearity and temperature behaviors the magnetoresistive current transducers can be substituted for similar Hall-sensor transducers. Moreover thin film GMR sensors are very convenient to prepare as integrated current transducers.

Fig. 4 illustrates the sensor package orientation for detecting the field from a current-carrying wire. This application allows for current measurement without breaking or interfering with the circuit of interest. The wire can be located above or below the chip, as long as it is oriented perpendicular to the sensitive axis. The review of GMR sensors for the measurement of electrical currents recently, conducted by Reig. et. al [36]. Recently, Wang *et al* [37] has integrated delta-sigma digital current sensor.

3.2. GMR for Position Sensor

Magnetic sensors are ideal for all kinds of contactless position registration, e.g. distance, speed, angle, rotational speed and sense of rotation [38]. The magnetic sensors based on GMR effect developed for position detection are now finding into industrial and automotive applications. GMR sensors have also been used in automotive applications such as rotation sensors [39]. GMR sensor can be used to count pulses generated by permanent magnet attached to the wheel or the motor for calculating their rotation.

3.3. GMR Head

The primary advantage of GMR head is its great sensitivity to magnetic fields, which makes it possible to detect smaller recorded bits and to read these bits at higher data rates. Larger signals from GMR heads also help overcome electronic noise. GMR heads have become the dominant head technology nowadays.

The magnetic recording process utilizes a thin film transducer for the creation or writing of magnetized regions (bits) onto a thin film disk and for the detection or reading of the presence of transitions between the written bits. The thin film transducer is referred to as a thin film head. It consists of a read element, which detects the magnetic bits and a write element which creates or erases the bits. Schematic of the tape showing longitudinal media with the written bits are shown in Figure 5, the transducer with an electromagnetic yoke-like structure to write a bit, and the structure of a shielded magnetoresistive film to detect "out of the plane disk" wild field originating from the transition.

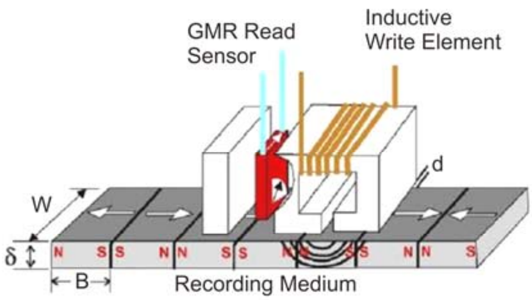

Fig. 5. Schematic of a magnetic recording head [40]

3.4. GMR Biosensors

Nowadays, accurate, rapid, cheap and selective analysis is required for clinical and industrial laboratories. Biosensors based on GMR material seem to be among the best candidates to meet these criteria. Since the late 1990s, magnetoelectronics [41] has emerged as one of several new platform technologies for biosensor and biochip development. This technology is based on the detection of biologically functionalized micrometer or nanometer-sized magnetic labels, using high-sensitivity microfabricated magnetic-field sensors.

The pioneering work in the field of magnetoresistive biosensors was done by the Naval Research Laboratory (NRL) [42, 43], which developed the first prototype magnetoresistive biosensor called bead array counter (BARC). It consists of 8 separate arrays, each incorporating 8 rectangular (5 μm × 80 μm) sensor elements per probe DNA spot. A single sensor element is capable of detecting a single magnetic marker (Dynal Inc., M-280, mean diameter 2.8 μm). They have shown good selectivity and sensitivity (10 times better than the unspecific signal) to an unspecified amount of single-stranded *Francisella tularensis* DNA oligomers [44].

A first model for the detection of magnetic markers by GMR-type magnetoresistive sensors was published by Tondra, et.al, 1999 in NVE Inc.[45]. He concluded that single magnetic markers of any size can be detected as long as the sensor has about the same size as the marker and the insulating protection layer is thin enough. Several groups have continued the research and development of magnetic biosensing technology [9, 46, 47, 48, 49, 50, 51]. A review of GMR biosensors and their use in clinical diagnosis has been carried out by Djamal, et al. [52, 53].

4. Conclusion

The GMR sensors are best candidates for future device based on lab-on a-chip, compact and inexpensive detection units. The GMR sensor measures electrical signal directly from the sensor, and makes a low-cost, highly portable device feasible. On other hand, GMR sensors are more sensitive, portable and give a fully electronic readout.

Acknowledgements

This work was (partially) supported by the Directorate for Research and Community Service, The Ministry of National Education Republic of Indonesia under grant No: 501/SP2H/PP/ DP2M/VI/2010.

References

[1] Daughton, J.; Brown, J.; Chen, E.; Beech, R.; Pohm, A.; Kude, W. Magnetic-field sensors using GMR multilayer. *IEEE Trans. Magn*. 1994, **30**, 4608-4610.

[2] Tsang, C. H.; Fontana, R; E, J.; Lin, T.; Heim, D. E.; Gurney, B. A.; Williams, M. L. Design, fabrication, and performance of spin-valve read heads for magnetic recording applications. *IBM J. Res. Dev.* 1998, **42**, 103–116.

[3] Daughton, J. M. GMR applications. *J. Magn. Magn. Mater.* 1999, **192**, 334–342.

[4] Inomata, K. Giant Magnetoresistance and Its Sensor Applications. *J. Electroceram.* 1998, **2 (4)**, 283–293.

[5] Mahdi, A. E.; Panini, L.; Mapps, D. Some new horizons in magnetic sensing: high-T_c SQUIDs, GMR and GMI materials *Sens. Actuators, A* 2003, **105**, 271–285.

[6] Giebeler, C.; Adelerhof, D. J.; Kuiper, A. E. T.; van Zon, J. B. A.; Oelgeschla¨ger, D.; Schulz, G. Robust GMR sensors for angle detection and rotation speed sensing. *Sens. Actuators, A* 2001, **91**, 16–20.

[7] Rieger, G.; Ludwig, K.; Clemens, W. GMR sensors for contactless position detection. *Sens. Actuators, A* 2001, **91**, 7–11.

[8] Hermann, T.; Black, W. C.; Hui, S. Magnetically coupled linear isolator. *IEEE Trans. Magn.* 1997, **33**(5), 4029–4031.

[9] Rife, J.C; Miller, M.M; Sheehan, P.E; Tamanaha, C.R; Tondra, M; Whitman, L.J. Design and Performance of GMR sensors for the detection of magnetic microbeads in biosensors. *Sens. Actuators A*. 2003, **107**, 209 – 218.

[10] Hall, D.A; Gaster. R.S; Lin,T; Osterfeld, S.J; Han, S; Murmann, B; Wang, S.X. GMR biosensors arrays: A system perspective. *Biosensors and Bioelectronics*. 2010. **25**. 2051-1057.

[11] Lecoeur, M.P; Parkkonen, L; Chollet, N.S; Polovy, H; Fermon, C; Fowley, C. Magnetocardiography with sensors based on giant magnetoresistance. Appl. Phys. Lett. 2011. **98**. 153705.

[12] Baibich, M.N.; Broto, J.M.; Fert, A.; Vandau, F.N.; Petroff, F.; Eitenne, P.; Creuzet, G.; Friederich, A.; Chazelas, J. Giant magnetoresistance of (001)Fe/(001)Cr magnetic superlattices. *Phys. Rev. Lett*. 1988, **61**, 2472-2475.

[13] Binasch, G.; Grunberg, P.; Saurenbach, F.; Zinn, W. Enhanced magnetoresistance in layered magnetic-structures with antiferromagnetic interlayer exchange. *Phys. Rev*. B. 1989, **39**, 4828-4830.

[14] Ramli, Mitra Djamal, and Khairurrijal, "Effect of Ferromagnetic Layer Thickness on the Giant Magnetoresistance Properties of NiCoFe/Cu/NiCoFe Sandwich" Proceeding *3rd Asian Physic Symposium* (APS) 2009, ISBN: 978-979-98010-5-0, Bandung, 22 – 23 July 2009. pp 65 – 67.

[15] Djamal, M, Ramli, Yulkifli, and Khairurrijal, "Effect of Cu Layer Thickness on Giant Magnetoresistance Properties of NiCoFe/Cu/NiCoFe Sandwich" Proceeding on *ICCAS-SICE* 2009 Fukuoka, Japan, August 18-21, 2009, pp. 365-368.

[16] Himpsel F J. Electronic states in magnetic nanostructrures. *IBM J. Res. Dev.* 1998. **42.** 33–42.

[17] Ranchal, R.; Torija, M.; L´opez, E.; S´anchez, M.C.; Aroca, C.; S´anchez, P. The influence of anisotropy on the magnetoresistance of permalloy–copper–permalloy thin films. *Nanotechnology*. 2002, **13**, 392-397.

[18] Mujika, M.; Arana, S.; Casta˜no, E.; Tijero, M.; Vilares, R.; Ruano-L´opez, J.M.; Cruz, A.; Sainz, L.; Berganza, J. Microsystem for the immunomagnetic detection of *Escherichia coli* O157 : H7. *Phys. Status Sol.* A 2008, **205**, 1478-1483.

[19] L´opez-Mart´ın, A.J.; Carlosena, A. Performance tradeoffs of three novel GMR contactless angle detectors. *IEEE Sens. J.* 2009, **9**, 191-198.

[20] Dieny, B.; Speriosu, V.S.; Metin, S.; Parkin, S.S.P.; Gurney, B.A.; Baumgart, P.; Wilhoit, D.R. Magnetotransport properties of magnetically soft spin-valve structures. *J. Appl. Phys*. 1991, **69**, 4774-4779.

[21] Hartmann, U. Magnetic Multilayers and Giant Magnetoresistance: Fundamentals and Industrial Applications; Springer: Berlin, Germany, 1999.

[22] Freitas, P.P.; Ferreira, R.; Cardoso, S.; Cardoso, F.; "Magnetoresistive sensors. *J. Phys.-Condens. Matter.* 2007, **19**(16), 165221.

[23] Slonczewski J C. Conductance and exchange coupling of two ferromagnets separated by a tunneling barrier. 1989. *Phys. Rev.* **B39**. 6995–7002.

[24] Xiao J Q . Giant magnetoresistance in nonmultilayer magnetic systems. *Phys. Rev. Lett.* 1992. **68 .**3749–3752.

[25] Berkowitz ,J. A. E. Giant magnetoresistance in heterogenous alloys. *Phys. Rev. Lett.*1992. **68 .**3745–3748.

[26] Xiao J Q. Giant magnetoresistive properties in granular transition metals. *IEEE Trans. Magn*.1993. **29**.2688–2693.

[27] Dieny B. Structural, magnetic and transport properties of $NiFe_xAg_{1-x}$ heterogeneous alloys. *J. Magn. Magn. Mat.*1994. **130** .197–215.

[28] Wang J Q and Xiao G. Transition-metal granular solids: microstructure, magnetic properties and giant magnetoresistance. *Phys. Rev.* 1994.**B49** 3982–3986.

[29] Parkin S S P. Giant magnetoresistance in as-grown epitaxial films of phase separated Co-Cu and Co-Ag. *Europhys. Lett.* 1993. **22** 455–462.

[30] Francis**.** ***T.L;*** Mermer**.*O;*** Veeraraghavan**.** ***G;*** Wohlgenannt**.** ***M.*** Large magnetoresistance at room temperature in semiconducting polymer sandwich devices**.** New J. Phys., 2004, 6, 185.

[31] Mermer. O; Veeraraghavan. G; Francis. T; Wohlgenannt. M, Large magnetoresistance at room-temperature in small-molecular-weight organic semiconductor sandwich devices. *Solid State Commun*, 2005, **134**, 631-636.

[32] Mermer. O; Veeraraghavan. G; Francis. T; Sheng. Y; Nguyen. D.T; Wohlgenannt. M; Kohler. A; Al-Suti. M; Khan. M. Large magnetoresistance in nonmagnetic π-conjugated semiconductor thin film devices. *Phys. Rev.B: Condens. Matter*, 2005, **72**, 205202.

[33] Tumanski, S . *Thin Film Magnetoresistive Sensors*. London. IoP Publishing, 2001.

[34] NVE Corporation. *GMR Sensors Catalog*. NVE Corporation: Eden Prairie, MN, USA, 2003.

[35] NVE Corporation. *Application Notes for GMR Sensors*; NVE Corporation: Eden Prairie, MN, USA, 2003.

[36] Reig, C; Beltran, M.D.C; Munoz, D.R. Magnetic Field Sensors Based on Giant Magnetoresistance (GMR) Technology: Application in Electrical Current Sensing. *Sensors*. 2009. **9**. 7919 – 7942.

[37] Wang, Z; Qian, Z; Huang, X. Delta-Sigma Digital Current Sensor Based On GMR. *J. Phys.: Conf. Ser*. 2011. **263**. 012009(1-7).

[38] Rieger, G; Ludwig, K; Hauch,J; Clemens, W. GMR sensors for contactless position detection. *Sens. Actuators A*. 2001. **91**. 7-11.

[39] Treutler.C.P.O. Magnetic Sensors for Automotive Applications. *Sens. Actuators A*. 2001. **91**. 1-6.

[40] Gurney, B. A. Giant Magnetoresistance in Magnetic Recording, *AAPPS Bulletin.* December 2008, Vol. 18, No. 6. 18-23.

[41] Prinz, G.A. Device Physics-magnetoelectronics, *Science*, 1998. **282**. 1660-1663.

[42] Baselt, D.R; Lee, G.U; Natesan, M.; Metzger, S.W; Sheehan, P.E; Colton, R.J. A biosensor based on magnetoresistance technology, *Biosensor and Bioelectronics.* 1998. **13**, 731-739.

[43] Edelstein, R.L; Tamanaha, C.R.; Sheehan, P.E.; Miller, M.M; Baselt, D.R.; Whitman, L.J; Colton, R.J. The BARC biosensor applied to the detection of biological warfare agents . *Biosensors and Bioelectronics*. 2000. **14**, 805–813.

[44] Miller, M.M.; Sheehan, P.E; Edelstein, R.L; Tamanaha, C.R; Zhong, L; Bounnak, S; Whitman, L.J; Colton, R.J. A DNA array sensor utilizing magnetic microbeads and magnetoresistive detection. *J. Magn. Magn. Mater*. 2001. **225**, 138–144.

[45] Tondra, M; Porter, M; Lipert, R.J. Model for detection of immobilized superparamagnetic nanosphere assays labels using giant magnetoresistive sensors. *J. Vac. Sci. Technol. A*. 1999. **18** (4), 1125–1129.

[46] Ferreira, H. A; Graham, D. L; Freitas, P. P; Cabral, J. M. S. Biodetection using magnetically labeled biomolecules and arrays of spin valve sensors. *Journal of Applied Physics* . 2003. **93**, 7281–7286.

[47] Reiss, G., Brueckl, H., Huetten, A., Schotter, J., Brzeska, M., Panhorst, M., Sudfeld, D., Becker, A., Kamp, P.B., Puehler, A., Wojczykowski, K., Jutzi, P. Magnetoresistive sensors and magnetic nanoparticles for biotechnology. 2005. *Journal of Materials Research*. **20**, 3294–3302.

[48] Xu, L, Yu, H, Michael, S. A, Han, S. J, Osterfeld, S, White, R. L, Pourmand, N, Wang, S. X, Giant magnetoresistive biochip for DNA detection and HPV genotyping. 2008. *Biosensors and Bioelectronics*. **24**, 99–103

[49] Osterfeld, S. J, Yu, H, Gaster, R. S, Caramuta, S, Xu, L, Han, S, Hall, D. A, Wilson, R, Sun, S, White, R. L, Davis, R. W, Pourmand, N, and Wang, S. X. Multiplex protein assays based on real-time magnetic nanotag sensing. 2008. *Proceedings of the National Academy of Sciences*. **105**, 20637–20640.

[50] Koets, M., van der Wijk, T., van Eemeren, J., van Amerongen, A., Prins, M., Rapid DNA multi-analyte immunoassay on a magneto-resistance biosensor. *Biosensors and Bioelectronics*. 2009. **24**, 1893–1898.

[51] Hall, D. A, Gaster, R. S. Lin, T, Osterfeld, S. J, Han, S, Murmann, B, and Wang, S. X. GMR biosensor arrays: A system perspective. *Biosensors and Bioelectronics*. 2009. **25**. 2051–2057.

[52] Djamal, M; Ramli; Yulkifli; Suprijadi; Khairurrijal. Biosensor Based on Giant Magnetoresistance Material. *International Journal of E-Health and Medical Communications*. 2010. **1**(**3**), 1-15.

[53] Djamal, M; Ramli; Haryanto, F; Khairurrijal. GMR Biosensor for Clinical Diagnostic. In: Serra, P.A. editors. *Biosensors for Health, Environment and Biosecurity*. Rijeka. InTech. 2011. p. 149 – 164.