GIANT MAGNETORESISTANCE (GMR): SPINNING FROM RESEARCH TO ADVANCED TECHNOLOGY

K.Y. Kok* and I.K. Ng

Malaysian Institute for Nuclear Technology Research (MINT),
Bangi, 43000 Kajang, Selangor Darul Ehsan, Malaysia

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ABSTRACT

In this paper, we aim to examine the research and development of materials demonstrating the giant magnetoresistance (GMR) property, a novel material property that has revolutionised the advances of magnetic sensor and mass-memory technology today. A comprehensive outline for the fundamental materials aspects as well as the physics of the underlying mechanisms behind the GMR property is given. Recent development of GMR materials in data storage industry and other potential technological applications exploiting the GMR property are also discussed.

1. INTRODUCTION

As the use of computers in daily work continues to proliferate, there is a pressing demand for higher data storage capacity and faster data processing capability in the era of digital information. The search for the successor to the currently available data storage science is always a challenging endeavor for material scientists and technologists alike. A promising progress in magnetic recording industry came in 1988 when two independent groups of scientists, headed by Albert Fert from Université Paris-Sud (France) and Peter Grünberg from KFA research institute in Jülich (Germany), observed an unexpectedly large change in electrical resistance when epitaxially grown Fe/Cr multilayers were subjected to external magnetic field^{1,2}. This remarkable property of materials, termed as giant magnetoresistance (GMR), was immediately recognised as the desired feature in the new generation of magnetic sensors, magnetic read heads and magnetic version of random access memory (MRAM) chips for improving the storage densities of the available recording media. Motivated by this profitable wide range of commercial possibilities, giant manufacturers in data storage industry around the world rapidly started an anxious race to put such material into use. Great enthusiasm also came from material scientists who were curiosity-driven for gaining fuller understanding of the physics behind the observed GMR property. Doubtless to say, GMR has today emerged as one of the hottest research topics in the field of magnetoelectronics-a recent

*Corresponding author - e-mail: kyk1000@mint.gov.my, Fax: 89250907, Tel: 89250510

advance in electronics which uses the electron's spin or magnetic moment, rather than its charge for logic, information storage and sensor applications.

2. THE MATERIAL

The discovery of GMR in magnetic multilayers prompted a new perspective on the magnetic sensor configuration that traditionally based on ferromagnetic films or alloys displaying anisotropic magnetoresistance (AMR) property. AMR is measured by the change in resistance when the angle which the current makes with magnetization in a ferromagnet changes. GMR, on the other hand, is measured by the percentage change in resistance when the magnetic moments of the successive ferromagnetic layers changes from antiparallel alignment state to parallel alignment state. Due to the fact that GMR effect is related to the magnetization of neighbouring magnetic layers, such effect is therefore not observed in homogeneous ferromagnetic film or alloy. GMR response in magnetic multilayers is only present for structures containing at least a trilayer arrangement with two magnetic layers separated by a spacer layer but not for structures containing one magnetic layer sandwiched between two spacer layers. The percentage change in resistance (normalized to saturation field resistance) in GMR materials can be ten times higher than that of AMR materials (typically only 2% to 4%).

The earliest GMR structure, which is the multilayer type, consists of artificial nanostructured bilayers formed from ferromagnetic transition metals (such as Fe, Co and Ni) alternating with either antiferromagnetic metals (such as Cr, Mn), non-magnetic transition metals (such as Ru, Pd, Mo, Ir) or noble metals (such as Cu, Ag, Au) as spacer layers³. The largest GMR response is usually found when the exchange forces couple the adjacent ferromagnetic layers antiferromagnetically at zero field; that is when the adjacent ferromagnetic layers possess anti-parallel orientation of magnetization. Despite exhibiting very large GMR response, the sensitivity (expressed by the resistance-field gradient of the GMR response) of these antiferromagnetic multilayers is low and not practical to use. In a sputtered antiferromagnetic Co/Cu multilayers for example, a 50-60% change in resistance requires a saturation field of ~ 1 T at room temperature. Such feature may not be practical in some applications like the magnetic read head where the material is expected to produce a large magnetoresistance change at low field in the range of 0.5-1 mT at room temperature. To overcome this problem, a "spin-valve" structure has been designed to induce much higher sensitivity and to allow greater control of the device magnetics as compared to the conventional repeating bilayer structure. A typical "spin-valve" structure comprises four films as shown in Figure 1: an antiferromagnetic (AF) film (e.g. FeMn), a ferromagnetic film (e.g. Co) which magnetic orientation is exchange-pinned by the AF film, a conducting spacer film (e.g. Cu) and a sensing film (e.g. NiFe) which responds to the external magnetic field⁴. The purpose of such arrangement is to attain antiparallel orientation of magnetization for the two magnetic films. Another variation for such structure is to use

Figure 1 : A magnetic read element of spin-valve structure.

two magnetic layers with different coercivities but without the pinning layer⁵. The two magnetic layers may be of the same composition but with different thicknesses so that the magnetization state of one tends to switch at lower external fields than the other. This is known as the pseudo-spin valve structure and has been a favourite candidate for the MRAM device.

GMR materials can be fabricated using most of the existing thin-film processing techniques such as molecular beam epitaxy (MBE), sputtering, vacuum evaporation or electrodeposition. Post-growth treatments including annealing and ion bombardment are commonly used to extrinsically improve the microstructures of the materials that are not prior developed during the fabrication process. Unexpectedly, the high quality and precise layer structure of the epitaxial multilayered films grown by the renowned molecular beam epitaxy (MBE) technique is found to be unmatched in GMR property as compared to the polycrystalline films produced by the less sophisticated ultra-high vacuum (UHV) sputtering method⁶. This observation has not been fully understood although it has been suggested that the degradation of the GMR effect in a MBE-grown multilayer film was due to magnetic short circuits, caused by the diffusion of magnetic atoms through pin holes in the non-magnetic spacer layers⁷. Despite the fact that the general principles of the GMR have been widely studied, there is still a lack of understanding of the factors controlling the magnitude of the GMR effect. Many structural features, such as, the nature of interface, vertical and lateral granularity, layer thickness and layer texture are reported to be responsible for the strength of GMR effect^{8,9}. Nevertheless, no convergent agreement has yet been reached on the structure-property relationship of the material. The microstructural study of the GMR materials is therefore crucial in providing insight to the observed GMR effect in these materials.

Due to the small length scales associated with the structural features of GMR materials, nanoscale characterisation techniques are needed to study the microstructural features of the materials. X-ray analysis, transmission electron microscopy (TEM) and atomic force microscopy (AFM) are among the characterisation techniques commonly employed. The layering structure of the materials can be probed using X-ray grazing incidence reflectivity while the information on atomic structure is retrieved by X-ray diffraction at high angles¹⁰⁻¹². X-ray diffuse scattering, on the other hand, is useful for obtaining the in-plane structural features, such as the interfacial roughness, the vertical and the lateral correlation lengths of the roughness¹³⁻¹⁴. For probing the localised microstructural features, TEM is used to investigate the cross-sectional and the in-plane microstructures of the materials while AFM reveals the surface morphology of the materials¹⁵⁻¹⁷. The general microstructures of a sputtered GMR multilayer, epitomized by the Co/Cu system, is illustrated schematically in Figure 2¹⁸. The associated microstructural features are revealed by the experimental X-ray diffractograms, TEM (bright-field) and AFM images. Additional information on magnetic structure of the material can be obtained using such techniques as polarised neutron reflectometry (PNR), magnetic force microscopy (MFM) and Lorentz microscopy¹⁹⁻²⁰. In recent years there have been many advances in the

Figure 2 : Schematic illustration for the general microstructures of a sputtered Co/Cu GMR multilayer. Dark arrows show the in-plane orientations of individual grains while grey arrows indicate the growth textures of the multilayer. The associated microstructural features are revealed by the experimental X-ray diffractograms, TEM and AFM images. (Each dark and grey arrow represents arbitrarily a specific in-plane and out-of-plane crystallographic direction respectively).

experimental techniques for probing both the structures as well as the magnetism of the multilayers. This has greatly improved the understanding of the structure-property relationship of the GMR materials.

3. THE SCIENCE

In contrast to the conventional magnetoresistance (MR) where an external field is used to influence the electron scattering from impurity and lattice imperfections, the large resistance change in GMR response is due to reorientation of magnetisation from antiparallel alignment to parallel alignment state of the magnetic layers of the material, brought about by the external field. The basis of GMR is that the electrons resistivity in the magnetic layers depends on the direction of the electron spin with respect to the orientation of the magnetization; electrons which have a parallel spin undergo less scattering and therefore have a lower resistance and vice-versa. Figure 3 illustrates this spin-dependent scattering in a Co/Cu multilayer system. An essential mechanism for GMR, spin-dependent scattering is a consequence of spin asymmetries between the spin-up and spin-down electrons of the ferromagnetic transition metals in the GMR materials.

Some interfaces, however, may also have spin asymmetries of their own. It is still a debatable issue on the origin of the GMR effect in a metallic multilayer: that is, whether

Figure 3 : Schematic illustration of the conduction electrons passing through a Co/Cu multilayer in (a) a low and (b) a high external field. At low field, conduction electrons entering the multilayers in antiparallel magnetization will be scattered into the available electron states at alternate magnetic layers (Co) regardless of their spin directions, thus producing a high resistance state. Under the influence of a high magnetic field, the magnetic moments in the magnetic layers are then parallelly aligned and the conduction electrons with the spin directions parallel to the orientation of the magnetic moment cannot find sites to be scattered into. There is, therefore, a low resistance channel for their movement throughout the multilayer, giving a low resistance state.

the spin-dependent scattering that occurs in the bulk, or that originated at the interfaces of the multilayer system actually determines the magnitude of GMR produced. In the case of an annealed Fe/Cr system for example, the increase in GMR when the multilayers are annealed was attributed to the effect of the strong spin dependence of electron scattering for Cr impurities in an Fe host²¹. The origin of this is Friedel-type scattering, the resonant scattering of the virtual bound state of a Cr atom in the d-band of Fe. This interface scattering, as commented by Hall et al.²², is not evident in the Co/Cu multilayer system. The spin-dependent scattering in the Co/Cu system appears to be predominantly of bulk scattering origin due to the split d-band of Co. Levy et al.²³ related the GMR of Fe/Cr multilayers to the spin-dependent interface potential while the same quantum-mechanical approach has also been used by Lenczowski et al.²⁴ to interpret the GMR effect in Co/Cu multilayers. In contrary, Edwards et al.²⁵ used a simple analytical formula, that was based on Boltzman equation, to show that spin-dependent s-d scattering into the split d-band of the magnetic layer is able to explain the observed effect in both Fe/Cr and Co/Cu systems.

The magnitude of GMR effect in a multilayer system oscillates with decreasing amplitudes as the thickness of the spacer layer increases, corresponding to the interlayer exchange coupling between the ferromagnetic layers that oscillates between the antiferromagnetic coupling and ferromagnetic coupling states²⁶. As a result, there are some thickness ranges of the spacer layer where magnetoresistance is enhanced. When the spacer layer thickness is large enough, interlayer coupling between the ferromagnetic layers is cut off effectively, forming an uncoupled GMR multilayer. The origin of this oscillating exchange coupling is still an area of controversy. This oscillatory coupling behavior was believed to be Ruderman-Kittel-Kosuya-Yosida (RKKY) type which was initially developed in the 1950s to describe the long range interaction induced by magnetic moments in a free electron gas. The discrepancy of the RKKY model is that the period of oscillation predicted is smaller than that experimentally observed. Coehoorn²⁷ suggested an "aliasing effect" between RKKY oscillation and discrete spacing of the interlayer atomic planes of the spacer layer. Bruno and Chappert²⁸ subsequently derived the oscillation period in terms of the topographical properties of the Fermi surface of the spacer layer. Gracia and Hernando²⁹ however proposed a quantum-well model that suggested the period of oscillation to be characteristic of the lateral scale of the interface inhomogeneities.

The magnetoresistance of a multilayer system can be measured either with current flowing in the plane of the multilayer (known as CIP-MR) or with current flowing perpendicular to the multilayers (known as CPP-MR). CPP-MR is higher than CIP-MR due to spin accumulation at the interfaces. However, CPP-MR measurements are difficult to perform due to the fact that they have to be carried out at cryogenic temperatures as superconducting contacts are used. Figure 4 shows a typical CIP-MR dependence on applied magnetic field for a GMR multilayer.

Figure 4 : Typical CIP-MR curves for a GMR multilayer:
 (a) antiferromagnetically-coupled multilayer
 (b) weakly antiferromagnetically-coupled multilayer associated with domain wall formation

Figure 5 : Details of a GMR device element

4. THE TECHNOLOGY

The discovery of GMR property opens the way to a new generation of simple, robust magnetic sensors and devices, for example, read heads for disc drives, isolators and control circuitry for electrical machinery. Low cost sensor can be constructed using Wheatstone bridge designed with the GMR materials placed between two flux

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concentrators made from soft adjacent layers (SAL) as shown in Figure 5. The flux concentrators produce directional field amplification by approximately the ratio of the length of the concentrators to the gap between them³⁰. One potential application of GMR sensor is for measuring changes in rotation of small magnetic fields that may be used to monitor the speed of a motor or the wheels in an antilock-braking system in a car³¹. This could be done by placing small magnets on the axle and measuring the rotational speed with a GMR sensing device. Other applications include solid state compasses, current sensors for safety power breakers and electricity meters, imaging detector for use in geophysical exploration and detection of landmines, defect detection using eddy-current mapping, currency detection and detection of motor vehicles for traffic control. These magnetic sensors have the advantage of measuring physical properties such as direction, presence, rotation, angle or electrical currents without actual contact to the medium being measured as they only detect changes in magnetic field that has been created or modified by the physical properties. As such, some signal processing is required for the output signal of these sensors for translation into the desired parameter. The concepts for a variety of GMR sensors are briefly discussed and illustrated in articles by Caruso et al., Heremans, Smith and Schneider³²⁻³⁴. Non-Volatile Electronics is, at the moment, the only commercial vendor for on-chip GMR sensors.

In the field of data storage, the current magnetoresistive (MR) elements used in read heads are sputter-deposited NiFe (permalloy) films. GMR multilayers are, however, candidates for new type of MR read heads that offer more sensitive magnetoresistive response. Besides exhibiting superior temperature stability, GMR sensors are able to offer signals 20-30 times larger than that of the permalloy MR sensors and, at the same time, linear over most of the operation range. In 1994, magnetic read heads fabricated using "spin-valve" structure have been demonstrated to be the world's most sensitive sensor for detecting computer data on magnetic hard disk³⁵. In 1997, IBM introduced the first GMR hard disk drive using "spin-valve" structure with capacity of 16.8 gigabytes (GB) storage density, marking a start in the transition from MR to GMR era in data storage industry³⁶.

Another challenge for GMR technology is to envisage a MRAM (magnetic random access memory) chip using GMR materials, replacing the conventional memory chip based on silicon capacitors and transistors. A MRAM is a single solid-state memory device that could store information magnetically and read it electronically. It exploits the spin rather than the charge of the electron and has the advantages of non-volatility, fast data accessibility, non-destructive read-out and high storage capacity. A proposed MRAM device consists of an array of magnetic plots cut in the top of a GMR pseudo spin-valve structure³⁷. Information is written by flipping the magnetisation of the plots and is read by sensing the resistivity of each plot. The "0" and "1" state depend on the relative magnetisation orientation of the magnetic layers.

5. LOOKING AHEAD

Research in GMR has brought about an important milestone in the data storage industry which has the largest application of GMR technology. This is attributed to the intensive and dynamic work carried out in order to understand the fundamental aspects of materials, physics and the underlying mechanisms behind the GMR property, as well as to tackle the problems of materials processing and device fabrication. Apart from the GMR materials, large magnetoresistance change is also offered by the spin-dependent tunneling (SDT) structure that uses a dielectric interlayer instead of the conductor interlayer in the GMR multilayer system. Metal oxides of perovskite structure also demonstrate spin-dependent scattering and huge change in magnetoresistance known as colossal magnetoresistance (CMR). This class of material has drawn much attention lately. A number of different compounds derived from LaMnO system may exhibit up to 10^6 % change in electrical resistance with the application of several teslas of external magnetic field³⁸. The drawback of CMR material being the saturation field is so large that it impedes the functioning of the material as a device. Research is underway to overcome this drawback and to make it commercially exploitable. Clearly, spin process in solid state materials retains the useful constituent in the present and future memory devices. The ongoing quest for spin-controlled devices for future electronic applications will continue to overcome the limitation of current data storage technology.

REFERENCES

1. Baibich, M.N., Broto, J.M., Fert, A., Nguyen, Van Dau F., Petroff, F., Eitenne, P., Creuzet, G., Friederich, A. and Chazelas, J., 1988. *Giant Magnetoresistance of (001)Fe/(001)Cr Magnetic Superlattices*. J. Phys. Rev. Lett, 61 (21), 2472-2475.
2. Binasch, G., Grünberg, P., Saurenbach, F. and Zinn, W., 1989. *Enhanced Magnetoresistance in Layered Magnetic Structures with Antiferromagnetic Interlayer Exchange*. Phys. Rev. B, 39, 4828-4830.
3. Heinrich, B. and Cochran, J.H., 1993. *Ultrathin Metallic Magnetic Films: Magnetic Anisotropies and Exchange Interactions*. Advances in Physics, 42(5), 523-639.
4. Dieny, B., Speriosu, V.S., Parkin, S.S.P., Gurney, B.A., Wilhoit, D.R. and Mauri, D., 1991. *Giant Magnetoresistance in Soft Ferromagnetic Multilayers*. Phys. Rev. B, 43, 1297-1300.
5. Shinjo, T, Yamamoto, H, Anno, T and Okuyama, T, 1992. *Magnetism and Magnetoresistance of Metallic Multilayers*. Applied Surface Sc., 60/61, 798-806.
6. Parkin, S.S.P., 1994. *Giant Magnetoresistance and Oscillatory Interlayer Coupling in Polycrystalline Transition Metal Multilayers*. Ultrathin Magnetic Structures II (Eds.: B. Heinrich, B. and J.A.C. Bland). Germany: Springer-Verlage.
7. Farrow, R.C., 1998. *The role of Molecular Beam Epitaxy in Research on Giant Magnetoresistance and Interlayer Exchange Coupling*. IBM Journal of Research and Development, 42 (1), 43-52

8. Kok, K.Y. and Leake, J.A., 1996. *Study of Structural Imperfections in Sputtered Co/Cu Multilayers*. Thin Solid Films, 275, 210-212.
9. Joyce, D.E., Faunce, C.A., Grundy, P.J., Fulthorpe, B.D., Hase, T.P.A., Pape, I. and Tanner, B.K., 1998. *Crystallographic Texture and Interface Structure in Co/Cu Multilayer Films*. Phys. Rev. B, 58(9), 5594-5601.
10. Telling, N.D., Guilfoyle, S.J., Lovett, D.R., Tang, C.C., Crapper, M.D. and Petty, M., 1998. *Evidence of Roughness Distributions and Interface Smoothing in Co/Cu Multilayers Deposited under Energetic Particle Bombardment*. J. Phys. D: Appl. Phys., 31, 472-481.
11. Babkevich, A.Y., Cowley, R.A., Goddard, P., Schlinkert, R., Murphy, B.M., Collins, S.P. and Hickey, B.J., 2000. *X-ray Diffraction Study of Co-Cu Superlattices*. J. Phys.: Condens. Matter, 12, 6755-6771.
12. Fullerton, E.E., Kelly, D.M, Guimpel, J., Schuller, I.K., Bruynseraede, Y., 1992, *Roughness and Giant Magnetoresistance in Fe/Cr Superlattices*. Phys. Rev. Lett., 68 (6), 859-862 .
13. Pape, I, Hase, T.P.A., Tanner, B.K., Wormington, M., 1998. *Analysis of Grazing Incidence X-ray Diffuse Scatter from Co-Cu Multilayers*, Physica B, 253, 278-289.
14. Holý, V, 1994, *Diffuse X-ray Scattering from Non-Ideal Periodical Crystalline Multilayers*. Appl. Phys. A, 58, 173-180.
15. Kok, K.Y. and Ng, I.K., 2001. *TEM Characterization of Co/Cu Multilayer System*. Bulletin of the Electron Microscopy Society of Malaysia (MicroSoM), 4 (1), 10.
16. Langer, J. Mattheis, R., Schmidt, S., Senz, St. and Zimmermann T., 1996. *Unexpected Growth of GMR Multilayers: <111> in-plane Texture and Grain Bundling in 5 nm Fe/(Co/Cu)₂₄*, J. of Mag. and Mag. Mat., 156, 19-20.
17. Aleszkiewicz, M., Kalinowski, R., Czajka, R., Polewska, W., Wawro, A., Baczewski, L.T., and Rauluszkiewicz, J., 1997. *STM/AFM Observations of Co/Cu Magnetic Multilayers*. Acta Physica Polonica A, 91 (2), 311-314.
18. Kok, K.Y., 1997. *Microstructural Analysis of Giant Magnetoresistive Multilayers*. Ph.D. thesis, U. of Cambridge.
19. Schwarzacher, W., Allison, W., Penfold, J., Shackleton, C., England, C.D., Bennett, W.R., Dutcher, J.R. and Falco, C.M., 1991. *Polarized Neutron Reflection Used to Characterize Cobalt/Copper Multilayers*. J. Appl. Phys., 69(7), 4040-4045.
20. Heyderman, L.J., Chapman, J.N. and Parkin, S.S.P., 1994. *Electron Microscope Observations of the Magnetic Structures in Magnetoresistive Multilayer Films*. J. Phys. D: Appl. Phys., 27, 881-891.
21. Fert, A. and Campbell, I.A, 1976. *Electrical Resistivity of Ferromagnetic Nickel and Iron Based Alloys*. J. Phys. F : Met. Phys, 6, 849-871.
22. Hall, M.J., Hickey, B.J., Howson, M.A., Walker, M.J., Xu, J., Greig, D. and Wiser, N., 1993. *Magnetoresistance of Co/Cu Superlattices Grown by Molecular Beam Epitaxy*. Phys. Rev. B, 47(19), 12785-12793.
23. Levy, P.M., Zhang, S. and Fert, A., 1990. *Electrical Conductivity of Magnetic Multilayered Structures*. Phys. Rev. Lett., 65, 1643-1646.

24. Lenczowski, S.K.J, Gijs, M.A.M., Giesbers, J.B., van de Veerdonk, R.J.M. and de Jonge, W.J.M., 1994. *Interpretation of the Giant Magnetoresistance Effect in Co/Cu(100) Multilayers with the Quantum Model of Giant Magnetoresistance.* Phys. Rev. B, 50, 9982-9988.
25. Edward, D.M., Mathon, J. and Muniz, R.B., 1991. *A Resistor Network Theory of the Giant Magnetoresistance in Magnetic Superlattices.* IEEE Transactions on Magnetics, 27(4), 3548-3552.
26. Parkin, S.S.P., Bhadra, R. and Roche, K.P., 1991. *Oscillatory Magnetic Exchange Coupling through Thin Copper Layers.* Phys. Rev. Lett., 66(16), 2152-2155.
27. Coehoorn, R., 1991. *Period of Oscillatory Exchange Interactions in Co/Cu and Fe/Cu Multilayer Systems.* Phys. Rev. B, 44, 9331-9337.
28. Bruno, P. and Chappert C., 1991. *Oscillatory Coupling between Ferromagnetic Layers Separated by a Nonmagnetic Metal Spacer.* Phys. Rev. Lett., 67(12), 1602-1605.
29. Gracia, N. and Hernando, A., 1991. *The Ruderman-Kittel-Kasuya-Yosida Spin Polarization in Finite System: Long Range Antiferromagnetic Polarization.* Nanomagnetism, 49-57.
30. Jardine, D.B., Mathur, N.D., Blamire, M.G. and Evetts, J.E., 1998. *Increased Field Sensitivity in Co/Cu Multilayers with Soft Adjacent Layers.* IEEE Trans. Mag. 34, 1297-1299.
31. Evetts, J., 1997. *Spin Doctors.* Cambridge Materials Eyes, Autumn, 3.
32. Caruso, M.J., Bratland, T., Smith, C. H. and Schneider R., 1998. *A New Perspective on Magnetic Field Sensing.* Sensors Magazine, 15 (12), 34-46.
33. Heremans, J., 1993. *Solid State Magnetic Field Sensors and Applications.* J. Phys D: Appl Phys., 26. 1149-1168
34. Smith, C.H. and Schneider, R.W., 2000. *Low-Field Magnetic Sensing with GMR Sensors, Part 2: GMR Sensors and Their Applications.* Sensors Magazine, 16 (10), 84-91.
35. Tsang, C., Fontana, R.E., Lin, T., Heim, D.E., Speriosu, V.S., Gurney, B.A. and Williams, M.L., 1994. *Design, Fabrication and Testing of Spin-valve Read Heads for High Density Recording.* IEEE Trans. Magn., 30, 3801-3806.
36. de Boeck, J. and Borghs, G., 1999. *Magnetoelectronics.* Physics World, April, 27-32.
37. Daughton, J.M., Pohm, A.V., Fayfield, R.T. and Smith, C.H., 1999. *Applications of spin dependent transport materials.* J. Phys. D: Appl. Phys., 32, R169-R177.
38. Mathur, N.D., Burnell, G., Isaac, S.P., Jackson, T.J., Teo, B.S., MacManus-Driscoll, J.L., Cohen, L.F., Evetts J.E. and Blamire, M.G., 1997. *Large Low-field Magnetoresistance in $\text{La}_{0.7}\text{Ca}_{0.3}\text{MnO}_3$ Induced by Artificial Grain Boundaries.* Nature, 387, 266-268.