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Designing and Modeling of Giant Magnetoresistance (GMR) Materials based Devices in Electrical Power and Biomedical Systems

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Abstract

This paper presents Designing and Modeling of Giant Magnetoresistance (GMR) Devices in Electrical Power and Biomedical Systems and the related materials. The GMR, inverse GMR, and Spin valve using exchange bias have been analytically derived and discussed from the designing point of view for optimizing the performance of the GMR based Devices in Electrical systems. More recently, GMR has been used in sensors, magnetic memory chips, and hard-disk read-heads. The usage of this in biomedical applications, such as biosensors, is another significant feature. In biomedicine, GMR biosensors have enormous potential, especially for wearable health monitoring devices and illness diagnostics. From a research perspective, it has been noted how useful the ideal film thickness and annealing temperature are in the appropriately selected multilayers for the creation of GMR-based devices. Researchers and designers working in this quickly developing subject might find the study helpful. This study also examines the modeling tools and simulation methods used in the design of GMR devices, emphasizing the significance of precision engineering in obtaining the required magnetic characteristics. It has also been addressed how GMR elements can be integrated with microelectronic systems to increase sensitivity and signal-to-noise ratios in real-world applications. All things considered, the study provides insightful information on recent developments and potential future directions.

Keywords: Giant magneto resistance (GMR) devices for electrical systems, Magnetic random access memory (MRAM), Inverse GMR, and Spin valve

INTRODUCTION

It has now been established that the Giant magneto résistance (GMR) material is now understood as the most suitable material for the design and creation of magnetic field sensing devices with high electrical potential and magnetic characteristics that are useful for a variety of applications, including head recording, data storage, linear and rotational position sensors, magnetic field sensor measurements, current measurements, and non-volatile magnetic random access memory (MRAM). OLEDs (organic light-emitting diodes) have recently been found to contain innovative GMR material based on organic material developed after accounting for Organic Magneto resistance (OMAR). Contrary to the conventional usage of metals and semiconductors as a spacer layer in the spin-valve, this organic material has already been employed as a spacer layer in GMR devices with spin-valve topologies. Even yet, several variables, such as interface scattering of

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ferromagnetic with a spacer and spin scattering from large atoms of the spacer material, limit the efficiency of the spin-valve.

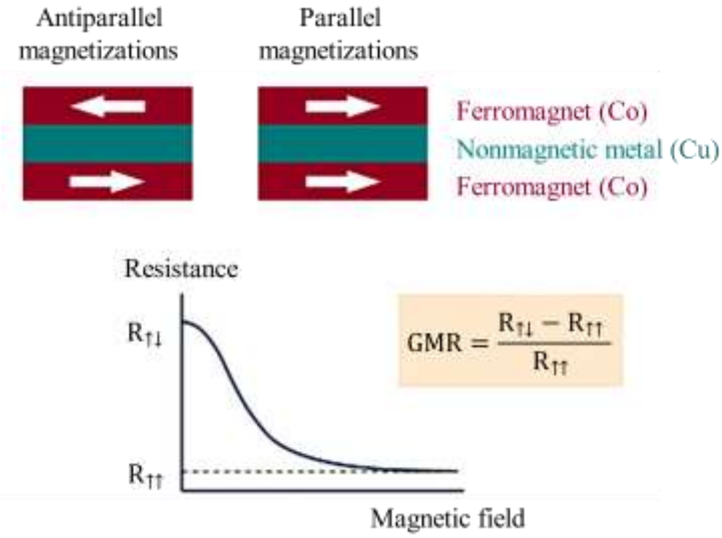

Figure 1. Structure of GMR device, and variation of Resistance with magnetization.

In the form of NiCoFe/Alq3/NiCoFe, have created a novel GMR material based on organic material [1]. The majority of data is still often stored magnetically, despite the growing use of CD-ROMs and the fact that electronic storage is also shown to be very appropriate for use in RAM.

It is noteworthy that this device can both write magnetic data to the ferromagnetic material and read magnetic data from it. To write magnetic data, the coil's current is passed proportionately to the desired signal. This aligns the spins in the ferromagnetic material and creates a magnetic field proportional to the current. The following Figure 1 illustrates the idea.

These days, electronic and computer systems make extensive use of this idea, which has greatly increased efficiency. The quantum mechanical magnetoresistance effect known as giant magnetoresistance (GMR) is seen in multilayers made up of alternating ferromagnetic and non-magnetic conducting layers [2]. Some of the materials found very useful for such devices and their experimental data are given below.

FeCr, $Co_{10}Cu_{90}$: δ_H = 40% at room temperature; and [110] $Co_{95}Fe_5$/Cu: δ_H = 110% at room temperature. [2] The operation is straightforward: when the material moves away from the coil, the magnetic field weakens, and the spins stay aligned until they are deleted by entering another magnetic field. Magnetic storage can be either analogue or digital, which sets it apart from electric storage. Recording analogue data with a continuously fluctuating current that creates a continually fluctuating magnetic field is possible. Digital data, on the other hand, is recorded by switching the current's direction. Reducing mistakes or data loss is crucial. The direction of magnetisation inside a domain alone does not determine binary data; rather, the shift in magnetic orientation between two domains does. The theory is straightforward: One bit of magnetic field with the same direction as the one before it indicates a 0 (no change), and one bit with the opposite direction indicates a 1 (change). As a result, it is evident that every piece begins with an orientation shift. However, since three domains of the same orientation cannot exist in a row, this data recording approach detects problems. The following Figure 2 provides some insight into domains, bits, and strings.

Moving the ferromagnetic material past the wire coil causes a change in the magnetic field, which in turn causes a current to flow through the coil proportionate to the change in the field. This process is the reverse of writing magnetic data. Since the magnetic field in the case of the 0 representation is constant between the two domains of a bit, no current is produced. [3] The magnetic field shifts from

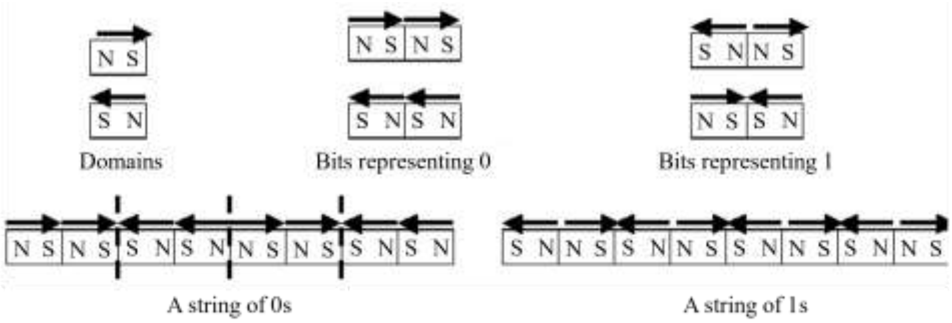

Figure 2. Demonstration of domains, bits, and strings.

one direction to the other for the 1 representation, though, which causes a current to flow through the coil. Though the Inductive reading of magnetic data in principle looks to be quite simple, it has two limitations: (i) the strength of the induced current depends on the speed of the material, and is greater if the ferromagnetic material is moved faster, thereby limiting the sensitivity of inductive read heads by the precision of the material speed; and (ii) the strength of the magnetic field, since an increase in the storage density, results in the shrinkage of the size of the data element, which implies that fewer electrons are contained in the region of one bit, and hence the associated magnetic field becomes smaller. This leads to the production of less change and therefore less induced current, which results in the requirement of more loops for producing a measurable current, thereby meaning more resistance, and hence more heat. These limitations are now being overcome by the use of the new magnetic storage devices based on the phenomenon of magnetoresistance for reading the magnetic data. By applying a potential difference to a wire positioned near the magnetic material on the disc or tape, magnetoresistance—a resistance brought on by the application of a magnetic field—is used to read magnetic data in computers. This property is directly proportional to the strength of the magnetic field.

As explained above, a reading of the magnetic field on the tape or disk is provided by monitoring the current varying because of the change in resistance caused by the passage of the magnetic fields representing data on the material by the wire. It must be noted that the discovery and application of the GMR phenomenon have provided us with the availability of economical and high density information storage for various applications in devices and research (2-13). [4] It has already made possible to develop the compact 160 GB Mp3 players and 1 TB hard drives, and is also helping in improving the capability and performance of such devices. Though the first breakthrough on GMR was provided by the Fert’s and Grünberg’s original papers, further research was carried out by IBM.

In addition to these Applications in Electronics and computers, these devices are also having applications in the medical field. Recent developments in GMR-based biomedical applications, such as disease diagnostics, genotyping, diet and drug management, brain and heart mapping, etc., are reviewed.

RESEARCH DESIGN OR METHODOLOGY

Anisotropic magnetoresistance and giant magnetoresistance are the two concepts that underpin the design of electrical devices based on GMR materials. [5] The two most significant applications are the storage media industry and hard drive spin valves. The British physicist Lord Kelvin originally described anisotropic magnetoresistance in 1857. He noted that resistance varies depending on the relative angle between the current and the conductor's magnetisation when a current is conducted through a magnetic conductor. It's interesting to note that it rises when the current is parallel to the magnetisation and falls when it is perpendicular. [6] Prior to the GMR's discovery, the phenomenon was explained by electron spin-orbit coupling and served as the foundation for hard drive reading. A thin layer of nonmagnetic material is positioned between two layers of magnetic material to form the Giant Magnetoresistance System. For the case of the Parallel magnetization, we can see that the up-spin electrons experience small resistance, whereas the down-spin electrons experience large resistance on the following Figure 3.

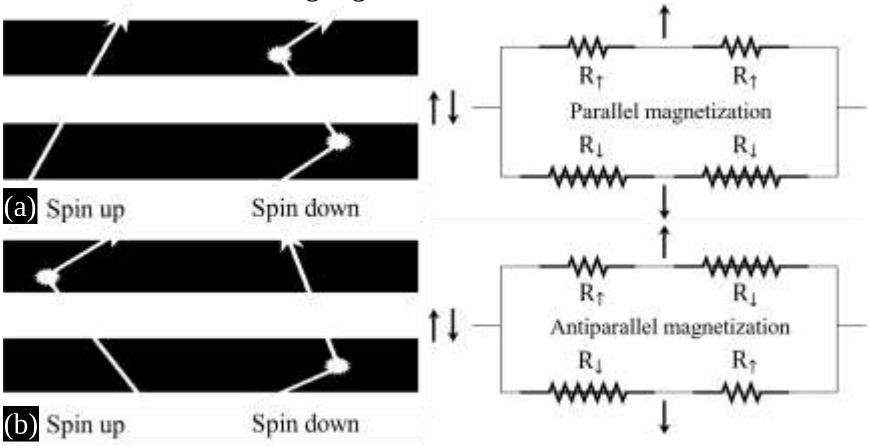

Figure 3. Parallel magnetization (a), and Antiparallel magnetization (b).

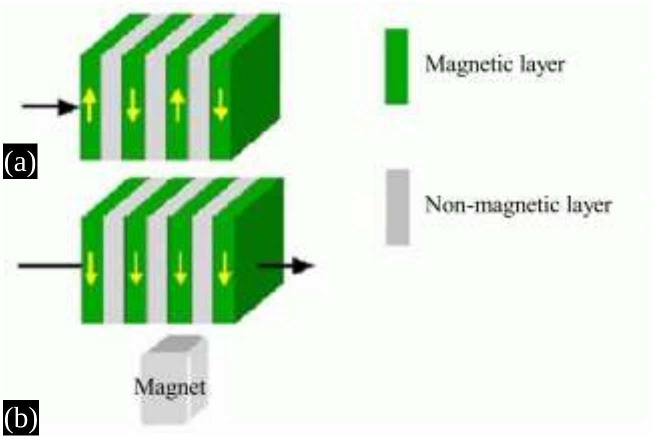

Figure 4. Giant Magneto Resistance (GMR).

Total resistance for the Parallel magnetization is given by:

$$R_{parallel} = \left(\frac{2R_{\uparrow}R_{\downarrow}}{R_{\uparrow}+R_{\downarrow}}\right) \tag{1}$$

It is evident that both electron spins in the antiparallel magnetisation situation encounter little resistance in one layer and a lot of resistance in the other. The overall resistance is determined by:

$$R_{antiparallel} = \frac{1}{2}(R_{\uparrow} + R_{\downarrow}) \tag{2}$$

Difference in resistance δR is given by:

$$\delta R = (R_{parallel} - R_{antiparallel}) = -\frac{1}{2}\left\{\frac{(R_{\uparrow}-R_{\downarrow})^2}{(R_{\uparrow}+R_{\downarrow})}\right\} \tag{3}$$

This expression unequivocally demonstrates that the difference between the resistance behaviour of spin-up and spin-down electrons is what causes the magnetoresistance effect. [7] Because of the ferromagnetic and antiferromagnetic interactions between the layers, it is evident that the magnetic ordering varies in the superlattices. By raising the ratio of the up-spin electron resistance to the down-spin electron resistance, the modulus of the difference in values can be raised. It's noteworthy to note that several organisations and for-profit companies have tried various coating methods for creating gadgets. While Fert and Grünberg employed the molecular beam epitaxy approach, which is more accurate but much slower, Stuart Parkin of IBM attempted to replicate the phenomenon using the sputtering technique. Interestingly, after experimenting with different sample compositions and layer thicknesses to better understand the GMR and integrate it into magnetic storage, Parkin's group was able to observe GMR in the first multilayer samples created. As seen here, GMR is created by alternating pg magnetic and non-magnetic layers.

Two spin-related conductivity channels that are connected to electron conduction and for which the resistance is either minimal or maximum can be used mathematically to explain the GMR phenomena. [8] The coefficient of the spin anisotropy, which is determined by utilising the minimum and maximum of the particular electrical resistivity for the spin-polarized current as shown below, is typically used to examine the relationship between the two.

$$\rho_{F\pm} = \left\{\frac{2\rho_F}{(1\pm\beta)}\right\} \tag{4}$$

where ρ_F rho is the ferromagnet's average resistivity. The resistance is lowest for the antiparallel orientation of the magnetisation in the layers in the case of the inverse GMR, which is seen when the magnetic layers are made of various materials, such as NiCr/Cu/Co/Cu. Additionally, the following formula can be used to represent the resistivity for electrons with opposing spins:

$$\rho_{\uparrow,\downarrow} = \left\{\frac{2\rho_F}{(1\pm\beta)}\right\} \tag{5}$$

It has distinct values, just as the spin-up and spin-down electrons' coefficients differ. The inverse GMR (16) is the result of the NiCr layer's contribution being greater than that of the Co layer in the case where it is not too thin. Note that the sign of the product of the coefficients in neighbouring ferromagnetic layers, rather than the signs of the individual coefficients, determines the GMR inversion [9]. Remarkably, the Inverse GMR is also seen when vanadium-doped nickel is used in place of NiCr alloy, but not when nickel is doped with iron, cobalt, manganese, gold, or copper [10]. The Spin valve with exchange bias is among the most significant uses of GMR.

It must be noted that the exchange bias generates the GMR effect in the most effective spin valves. A sensitive layer, a fixed layer, and an antiferromagnetic layer make up these devices. The antiferromagnetic layer is employed to freeze the magnetisation direction in the fixed layer. It must be determined that the antiferromagnetic and sensitive layers are relatively thin to lower the structure's resistance; the thickness is such that the film is mechanically robust. The valve responds to the application of an external magnetic field by altering the direction of magnetisation in the sensitive layer for the fixed layer (19). It should be mentioned that these spin valves differ from previous multilayer GMR devices primarily in that their amplitude of effect depends monotonically on the thickness of the non-magnetic layers, as shown by:

$$\delta_H(d_N) = \delta_{H0}\left\{\frac{exp(-d_N/\lambda_N)}{(1+d_N/d_0)}\right\} \tag{6}$$

Here δ_{H0} is a normalization constant, λ_N is the mean free path of electrons in the non-magnetic material, and d_0 is effective thickness which includes interaction between layers (19,20). The following relation provides the reliance on the ferromagnetic layer's thickness:

$$\delta_H(d_F) = \delta_{H1}\left\{\frac{1-exp(-d_F/\lambda_F)}{(1+d_F/d_0)}\right\} \tag{7}$$

It's interesting to note that, although for the ferromagnetic layer [11] these parameters have the same meaning as the previous equation. Although the magnetisation of an ensemble of superparamagnetic particles is zero, as is the case with a paramagnetic arrangement of very large spins, it is important to note that a superparamagnetic particle has all of its spins aligned internally, but the thermal energy continuously flips the magnetic orientation of the entire particle.It is important to note that the GMR is different from the Tunnel Magnetoresistance (TMR) in that it has metal spacer, whereas the TMR has insulating spacer. [12] Theory of Magnetism tells that the force on a current-carrying wire in a perpendicular magnetic field is due to the force on the charge carriers moving through the wire, which produces an increased resistance as the charge carriers have more collisions with atoms in the wire, the phenomenon being called magnetoresistance. However, the spin-dependent effect is much stronger than the effect of regular magnetoresistance, and that is the reason that it is called giant magnetoresistance, though it is a completely different effect. For the Magnetic Storage Media, we need about a hundred particles per bit, particles being of 50 nm to 10 nm e.g. CoPt particles (≈ superparamagnetic limit).

While considering Magnetization, the designer has to focus on various types of Anisotropy like (i) Magnetic Anisotropy, which is the energy to rotate the Magnetization; (ii) Crystalline anisotropy, where the magnetisation prefers to align with a particular crystallographic direction (such as the hexagonal axis in cobalt); (iii) Surface anisotropy, where the magnetisation is at a surface/interface and is frequently perpendicular to the interface (opposite to the shape anisotropy); and (iv) Shape anisotropy, where the magnetisation prefers to be parallel to the axis of a needle-shaped particle or in the plane of a thin film. Additionally, the characteristics of the material must be taken into consideration while selecting the material for the various components utilised in the production of the device. e.g. the Hard magnet has large anisotropy; Soft magnet has small anisotropy; NdFeBis used for Permanent magnet ; Co is used for storage medium, pure Fe is used for Transformer core , and perm alloy is used for sensor. Since magnetoresistance depends on the field rather than the change of field, it offers greater accuracy than induction. [13] As a result, its application is less reliant on the exact speed of magnetic material. Furthermore, compared to detecting induction, magnetoresistance requires far simpler circuitry. To get an understanding, we need to know that in the first situation, one wire loop with a potential difference applied and connected to an ammeter is used, while in the second case, several wire loops designed to maximise induced current and coupled to an ammeter are needed. Measured by dividing the change in resistance or changes in current by the storage medium's magnetic field, the effect's magnitude is approximately 4% in magnetoresistance heads and 1% in inductive heads. The uncertainty principle can also be used to study magnetoresistance theory. Due to the spin property, we are aware that electrons possess inherent magnetic fields. However, only one axis of the magnetic field may be measured at a time due to the uncertainty principle. Naturally, in the case of the unmagnified material, half of the electrons have spin that is positive along the selected axis (spin-up), while the other half have spin that is negative (spin-down) [13].

Since electrons with spins in the same direction as the magnetic field encounter fewer collisions than electrons with spins in the opposite direction, the underlying physics of a ferromagnetic material magnetised along the selected axis in the positive direction permits a spin-up electron to pass through the material more readily than a spin-down electron. By taking into account the band structures of ferromagnetic materials, this phenomenon can be better understood. In a homogeneous piece of magnetised material, the property of electron collisions is unclear. This is since conduction electrons are not magnetised because they enter the material through non-magnetized connecting connections [14].

Regardless of how the material is magnetised, half of the conduction electrons encounter more collisions than the other half, which maintains the material's resistance constant because roughly half of the electrons have spin-up and half have spin-down. The net effect is null because the spin-up electrons have a horizontal component of spin that is directed to the right, while the spin-down electrons have a horizontal component of spin that is directed to the left. The former have greater mobility, while the latter have less [15]. Phenomenon of the GMR in Ferromagnetic Material (FM) with Non-ferromagnetic material (NFM) spacer is illustrated in the following Figure 5.

The demagnetized conduction electrons, marked with short lines in the middle, move through the material for the FM case (Top); and across the lattice for the NFM case. However, for the case of the material being layered, the resistance is observed to change dramatically, resulting in the giant magnetoresistance phenomenon. It is evident that the layers of some ferromagnetic materials, which are separated by non-ferromagnetic materials, have alternating-direction magnetisations. These structures are known as magnetic superlattices and are made up of numerous layers. Nevertheless, there is no benefit

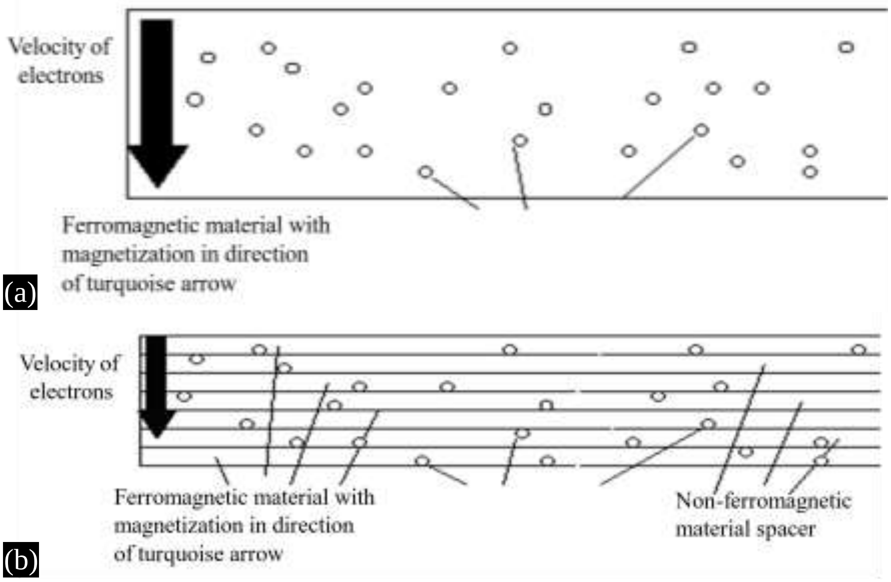

Figure 5. Illustration of GMR in Ferromagnetic Material (FM) with Non-ferromagnetic material (NFM) spacer.

to this superlattice over the single domain scenario. It goes without saying that the unmagnetized conduction electrons scatter as they go through this material's layers. Remarkably, electrons with left-spinning electrons scatter more in the top and third layers, whereas electrons with left-spinning electrons scatter more in the second and bottom layers. As a result, just like in the single domain case, the spin-related effects on resistance cancel out for the superlattice. But when the superlattice is placed in a magnetic field, the magnetisation of every layer aligns with the external field. As a result, only the conduction electrons with spins towards the left experience a higher rate of scattering, which lowers the material's resistance. Understanding the relative magnitudes of the different types of resistance is crucial. For example, inductance has a 1% effect, standard magnetoresistance has a 4% influence, and gigantic magnetoresistance has a 100% effect.

RESULTS AND DISCUSSION

Giant magnetoresistance's large magnitude has been discovered to be very helpful for magnetic reading devices because, like conventional magnetoresistance, it can be used to read magnetic data by monitoring the change in current as magnetic data passes by the superlattice. Since the largest effects are seen at low temperatures, research is currently being done to produce sensitive lattices at a reasonable cost as well as to get large huge magneto resistance effects at room temperature. Spin valves, which are lattices with only two ferromagnetic layers separated by a single spacer, have already been successfully used to achieve enormous magnetoresistance and have proven to be highly beneficial for computer integration [16].

Hysteretic loops for several Metal M1/Metal M2 for different thicknesses of the metallic layer are also very important inputs for the designer of the GMR based devices (22). It is clear that as the thickness of Cr layer increases, the peak of GMR increases, and also the rise becomes steeper. Thus, the designer has to choose the right thickness of the proper combination to achieve the optimum results. It has also been realized that in the multilayers devices, the role of the metallic layer is very important. The optimisation of the film thicknesses has been the subject of numerous investigations [17].

Though the widely accepted value is ~ 8 Aº - 12 Aº, still it is recommended that the designer has to reach these values on the basis of the own experiments. It has been reported that films of thickness 11 Aº and 9 Aº, for Co and Cu respectively provide good results. These results as reported in the literature have been reproduced below.

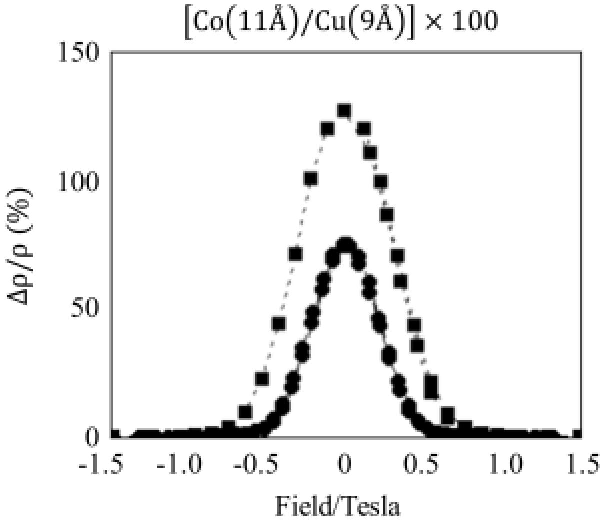

Figure 6. Dependence of $(\Delta\rho/\rho)$ on magnetization.
(Figure courtesy www.stoner.leeds.ac.uk.)

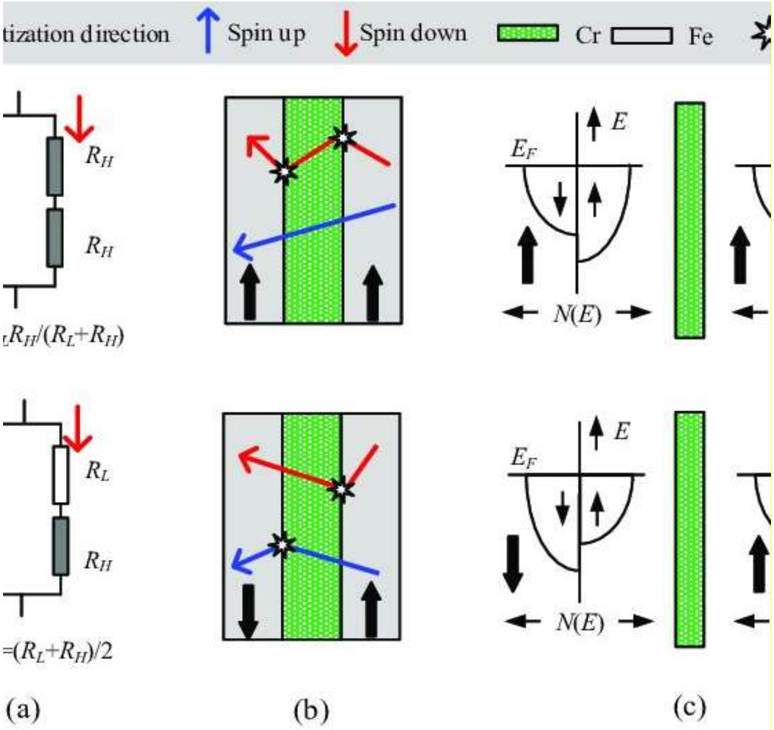

Figure 7. (a) Figure 1: Resistor model diagram; (b) Spin-dependent scattering diagram at ferromagnetic and non-ferromagnetic layer interfaces with parallel and anti-parallel magnetisation (PM and APM); (c) Electronic state density diagram with PM and APM. N(E) is the density of states; EF is the Fermi level; and E is the electron energy.
(Figure courtesy of Shen et al., Sensors, 18(1):148, January 2018).

Antiferromagnetic coupling is the parameter for which the spacer layer thickness is optimized. [18-19] The figure makes it evident that the sample with 9Å thick Cu spacers has the strongest antiferromagnetic coupling in terms of GMR. As anticipated, the sensation of the coupling between the two layers fluctuates in the case of the extremely thin spacer layer; that is, for some specific values of the spacer thicknesses, the magnetisations of adjoining layers naturally tend to arrange in opposite directions. Interestingly, though, if a strong enough magnetic field is applied, the layer magnetisations can be oriented along the field direction. [20-24] This obviously enables the two distinct resistance states to be obtained, which promotes the formation of the multilayered structures known as superlattices. These are samples that have a magnetic layer and a non-magnetic spacer repeated numerous times, such as {Co/Cu} x 30, with a thin Cu spacer separating each magnetic Co layer from its neighbours. Additionally, it can be seen that the resistance is large at zero field because all of the Co layers align antiparallel, and they continue to align until the sample is saturated when the magnetic field is applied [25–29].

It is evident that at fields greater than this, the resistance is at its lowest. The lower curve is at room temperature (around 300K), whereas the higher curve is measured at 4.2K. The GMR at ambient temperature has been found to be 75%, whereas the GMR at 4.2 K is 130%. [21] As a result, the temperature at which the gadget must be utilised is crucial. The annealing temperature is another crucial factor that the designer of the GMR-based devices must take into account. In contrast to the situation of As-deposited multilayer, it is found that the GMR increases as the annealing temperature rises, for example, from 300 °C to 325 °C. However, GMR is observed to diminish when the annealing temperature rises to 350 °C. To get the best results, the designer must select the appropriate annealing temperature for the multilayer combination used in the GMR-based device [30–34].

The advancements of integrated GMR technology for in vivo/vitro bio magnetic source imaging have been discussed who also show how integrated GMR may be used for biomagnetic field detection. Below is a reproduction of their model's schematics and associated setups.

CONCLUSION

As is now widely known, the Giant Magnetoresistance (GMR) is a quantum mechanical magnetoresistance effect that occurs in thin film structures made up of alternating ferromagnetic and nonmagnetic layers. When a magnetic field is present, the electrical resistance significantly decreases by about 10–80%. The choice of substrate material is crucial for producing metallic multilayers for the purpose of researching their magnetic characteristics; silicon, silicon dioxide, magnesium oxide, and aluminium oxide are all viable options. The designer must make sure that (i) the lattice parameters for the various metallic layers match one another and (ii) the two metals that compose the multilayer ideally have the same crystal structure in order to create a well-behaved metallic multilayer.

It has been found that chromium and iron are most suitable since both these metals have the bcc crystal structure, along with having very similar lattice spacing. Efforts are now being focused on making spintronic devices based on semiconductors, because in principle, they provide amplification, and generally serve as multi-functional devices, and also more importantly, can be more easily and conveniently integrated with the traditional semiconductor technology. Because of the tremendous utility of GMR in device fabrication for important applications, especially in high density information storage for various applications in devices and research, much research activity has been noticed during the last decade on GMR and the related topics. Giant tunnelling magnetoresistance at room temperature with MgO(100) tunnel barriers, and Giant room-temperature magnetoresistance in single crystal Fe/MgO/Fe magnetic tunnel junctions, are two significant papers on the subject.

The researcher has made some detailed studies on new materials, applications of organic semiconductors in spintronics, Magnetic Tunneling Junctions, and Hybrid Ferromagnetic Nanostructures. More recently have designed highly efficient GMR spintronic device exhibiting the highest magnetoresistive ratio based on two-dimensional MXene (Mn_2NO_2). Thus, it can be concluded that the field of GMR devices, especially for the improved performance has been drawing the attention of many researchers, and thereby has been evolving rapidly. By examining the super paramagnetic behaviour of magnetisation, Researcher have examined the particle size distributions in Co–Al–O insulating granular films with different Co concentrations (xCo). They have compared the particle size distributions estimated from the magnetisation analysis and the TEM observation, and they have demonstrated that it is possible to differentiate between the topological size and the magnetic size of particles.

The magnetoresistance (MR) ratio decreases slightly with xCo for xCo>36 at%, which is different from the result for metallic granular systems where the MR ratio drastically decreases with the coarsening of magnetic clusters. They have also proposed that some Co particles couple ferromagnetically to form larger magnetic clusters as xCo increases. A tuneable GMR magnetic field sensor that enables voltage tweaking of the linear range and sensitivity was created.

Researcher designed and developed open-loop current sensor based on giant magnetoresistance (GMR) effect in magnetic multilayered systems . More recently have reviewed the advantages and drawbacks of spintronic devices used in biomedical applications Thus, it can be concluded that the field of GMR devices, especially for the improved performance has been drawing the attention of many researchers, and thereby has been evolving rapidly.

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