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Technical Note and Brief Overview of the Materials Science and Technology along with Designing Aspects for Development of Spintronic Devices with Optimum Efficiency

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Abstract

One of the major challenges in designing and fabricating Spintronic devices is the choice of both, Materials and the Technology, along with understanding the intricacies of the Designing aspects. In this communication, we have attempted to briefly discuss these factors, with an aim to draw the attention of the Materials Scientists and Technologists to this serious challenge, in the direction of which, though a lot of research and development work has been done, still needs more concerted efforts to be made in order to make the Spintronic devices that can offer good efficiency for maximizing their usefulness.

Keywords

Materials Science Technology and Designing Aspects of Spintronic Devices, Epitaxial growth, Double Ion Beam Sputtering Technique, Magnetic Tunnel Junctions, Giant Magneto Resistance

1. Introduction

In the last two decades, the utility of Spintronic devices has been well established in various fields including next generation Information Technology, which has led to a large number of Research efforts in their development, especially in view of their superiority over Electronic devices.

In spite of great potential advantages, spintronics has to overcome many challenges, like generation of fully spin-polarized carriers (pure spins) and injection of spin into devices, long distance spin transport, and manipulation and detection of carriers' spin orientation. This is possible only by the development of device by using optimization techniques, and also designing new spintronics materials with specific properties. In addition, the spin scattering at the metal-metal or metal-semiconductor interface is also important and mist be taken care of.

The main obstacle in making Spintronic devices available for more important applications, is the choice of the appropriate materials and Techniques for coating them, which has to be made carefully along with the Optimization of the Designing them.

In the recent years, Spintronics has drawn the attention of many workers. Chopra [1] [2] [3] [4] [5] has studied in detail the Theoretical Aspects and Characteristics of GaMnAs Digital Alloys, Mathematical Modeling of Spintronic Devices, Organic Semiconductors and their Technical Applications in Spintronics, Mathematical Aspects of Spin-related Phenomena Models and the Associated Criteria for Spintronics, and Designing and Modeling of Devices based of Giant Magnetoresistance (GMR) Materials.

Some important studies on topics like Spin control [6], Spin orientation [7], Phenomenology of current-induced dynamics in antiferromagnets [8], Hydrodynamic theory of coupled current and magnetization dynamics in spin-textured antiferromagnets [9], and Spintronics of antiferromagnetic systems [10], have also been reported in the literature.

1.1. Choice of Material

Appropriate Material has to be chosen for the particular device. There are many kinds of materials useful for different Spintronic devices including Ferromagnetic metals—Fe, Co, Ni metals, and also their alloys. They are the most common spintronics materials which are used for making devices like spin valves and magnetic tunnel junctions. However, they can provide only partial polarization. Therefore, new spintronics materials: 1) ferromagnetic metals, 2) half metals, 3) Topological insulators (TIs), 4) HSCs, 5) SGSs, and 6) BMSs, have been recently employed for suitable use in various Spintronic devise. In case of Half-metallic ferromagnets (HMFs), the fundamental characteristic lies in the electronic structure in the sense that while one spin channel possesses metallic conduction, the other spin channel is insulating or semiconducting; as a result, the HMFs can intrinsically provide single spin channel electrons, and so spin polarization of 100% can be achieved.

Half metals, in the form of half-metallic antiferromagnets (HMAFMs) can also provide 100% spin-polarized electrons. Topological insulators (TIs) like HgTe and Bi1-xSbx are a unique type of insulators, which are insulating in their bulk, but metallic on their surface. It is to be noted that the spin-up and spin-down electrons propagate in opposite direction on the surface. They can work only at low temperatures, and require a lot of research work to be done before they can find practical applications.

Magnetic semiconductors, combine the properties and advantages of both magnets and semiconductors, and hence form the basis for spintronics devices. Magnetic semiconductors can be applied for 1) spin generation and injection, and 2) spin manipulation and detection.

1.2. Technology of Coating

The Technique for coating thin films required for the device has to be appropriate for making the device. In many cases, Epitaxial growth of films [11] is required. However, in most of the cases, Use of Dual IBSU [12] [13] for controlling Scattering, and thus Spin of the layers is the most suitable, for which Requirement of clean room facilities like clean air shower, and clean cloth coats etc: is a must. It has to be realized that with DIBS Unit, the packing density (Ratio of the volume of the coating material to the volume of the coated layer) is unity, and therefore the structure of the coating is uniform at atomic scale, without any voids, thus resulting in the uniform spin orientation of the film, and hence optimum efficiency of the device.

2. Designing Considerations for Spin and Tunneling Effect

It has now been well understood that by integrating the magnetic materials and impurities into nanoelectronic devices, it is possible to use the electron spin, and also its charge, for carrying information. This novel dimension in information processing devices is called Sspintronics, being somewhat similar to electronics. The designing and making of functional spintronic devices is based on the research and development of new materials and integration of different materials having atomic-level control. In this study, we focus on the case of Magnetic tunnel junctions (MTJs), which are considered as prototypical spintronic devices, and mainly consist of three layers: a ferromagnetic metal, an insulator, and another ferromagnetic metal. There are many types of structures of TMR MTJs, consisting of various layers of different materials like Co, Fe, MgO, Ru, CoFe, CoFeB, MnIr, TaN, Ta, and SiO_2. A simple Structure of MTJ is shown in **Figure 1**.

It has to be noted here that the insulator is just a few nanometers thick, such that it is thin enough to allow tunneling of electrons from one metallic electrode to the other. Interestingly, on aligning the magnetizations of the ferromagnetic layers, the tunneling current is large and hence the device resistance is quite low. On the other hand, when the magnetizations of the ferromagnetic layers are anti-aligned, the tunneling current is small and the device resistance is quite large. The working principle is simple: When the magnetization of one electrode is fixed by exchange coupling to a neighboring antiferromagnet, and the other layer is made to switch depending on an applied magnetic field, the MTJ shows Magnetoresistance, in which the resistance of the device is dependent on the sign of the applied field. This is the reason that the MTJs are commonly used as sensors in the read heads of magnetic hard disk drives. Another point to be noted is

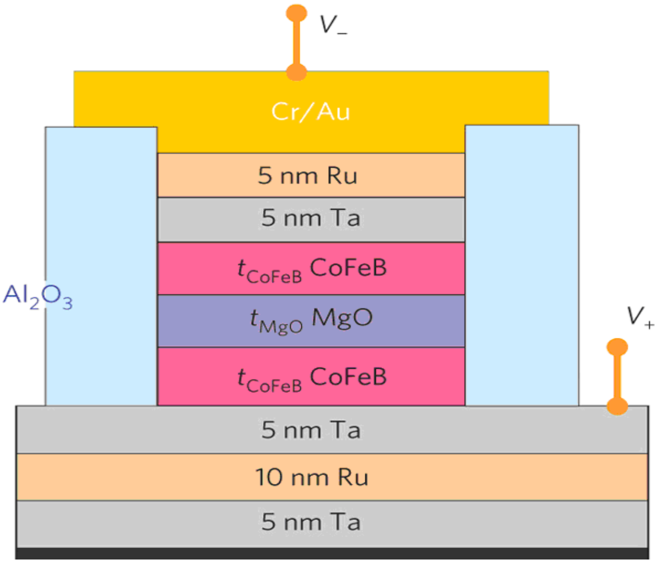


Figure 1. Simple Structure of MTJ = Schematic of an MTJ device for TMR.

that Half-metallic antiferromagnets (HMAFMs) work on the principle that for a half metal with stoichiometric composition, the spin magnetization per unit cell should be an integer in units of Bohr magneton, which can be zero after careful design. This fact has to be considered by the Device designer, while making the device.

2.1. Designing Aspects of Spintronic Devices

Magnetoresistance, Magneto Tunneling Junction (MTJ), and Tunneling Magnetoresistance (TMR) are mainly the Parameters for designing the Spintronic devices. These have to be chosen and optimized for the particular spintronic device. In many cases, there is a difference in the theoretical value and the achieved value, and so correction has to be applied by the feedback from the achieved value. This requires the experience and expertise of the designer. Sometimes, two or more iterations have to be done.

Magnetoresistance is as a result of the dependence of the electrical resistance of a sample on the strength of an external magnetic field, which is usually given by the following expression:

$$\delta H = \{R(H) - R(0)\}/R(0) \tag{1}$$

where R(H) is the resistance of the sample in a magnetic field H, and R(0) is the resistance of the sample for H= 0.

The MTJ consists of an insulator sand witched between two feromagnets; one in parallel and the other in antiparallel configuration. The Tunneling Magnetoresistance is given by:

$$\text{TMR} = \{(\text{Rap} - \text{Rp})\}/\text{Rp} \tag{2}$$

where Rap is the resistance for the antiparallel configuration, and Rp is that for the parallel configuration. Thus, it is clear that the TMR can be increased by increasing the difference between Rap and Rp. It has been established that the Magnetoresistance (MR) depends on the applied field. The resistance is low/high when the polarization of the magnetic layers is parallel/antiparallel.

The designer has to optimize the value of TMR, by selecting the proper electric field, and also considering the values of Rap and Rp.

2.2. Modeling for Tunneling Regime

This model is based on the assumption of shallow parabolic barrier, and the tunneling regime is on the basis of having the parallel and anti-parallel configurations. Transmission probability through a parabolic barrier is given by:

$$\mathrm{T} = \exp\left(\frac{-2 \text{ sq. of } \pi.\text{m.sq. root of EH.L}}{\text{L raise to power } 3/2\,\mathrm{h}}\right) \tag{3}$$

where EH is the height of the barrier, and L is the thickness of the barrier, m* the effective hole mass, and h the Planck's constant. It may be noted here that in GaAs, m* ≈ 0.5 mo where mo is the free electron mass. Also,

$$\beta = \left\{\frac{(\text{EFup} - \text{EFdown})}{(\text{EFup} + \text{EFdown})}\right\} = \left\{\frac{\Delta\text{Espin}}{(\text{EFup} + \text{EFdown})}\right\} \tag{4}$$

where β is the spin polarization.

3. Results and Discussion

The integration of two types of materials has been found to be useful for MTJ Devices. These are:

1) With negative spin polarization (Fe_3O_4 and Fe_4N) so that the spins of the conduction electrons are anti-aligned to the magnetization of the material. It is to be understood that MTJ with one negative spin polarization electrode, and one positive spin polarization electrode shows negative magnetoresistance, which can be used with a normal MTJ to make a three state device or a combined high gain sensors.

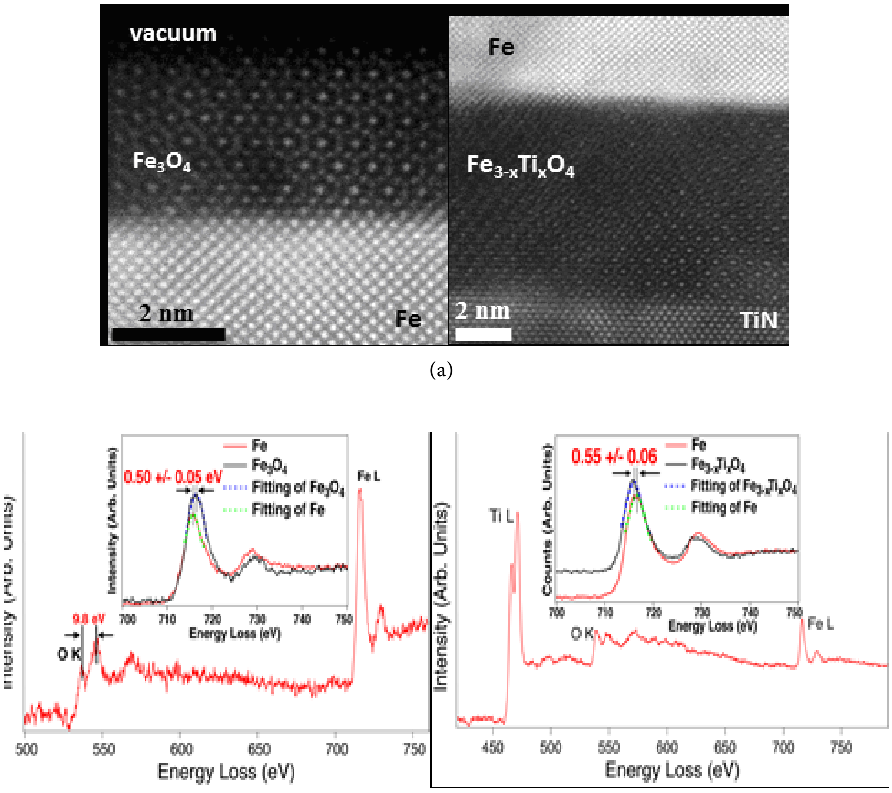
2) Huesler alloys: These materials are intermetallic phases in the L21 structure, termed as half metals, with a unique characteristic that only one spin band crosses the Fermi level, which implies that the current is in principle 100% spin polarized, and hence has the ability to make devices with extremely high magnetoresistance ratios. An important Huesler alloy is Co_2MnSi, in MTJs with an MgO tunnel barrier. The efficiency of a Co_2MnSi depends on the interface termination with the MgO. It has been observed that only the MnMn/O termination preserves 100% spin polarization in the tunneling current. In most of the other terminations, spin polarization reduces either partially (CoCo/O interface) or completely (MnSi/O interface). Xiang *et al.* [14] have done the Synthesis of Fe_3O_4 thin films by selective oxidation with controlled oxygen chemical potential. It is important to get an idea about the Fe_3O_4/Fe interface, Fe_3-xTixO_4 at the Fe/TiN interface, for the synthesis of the Spintronic devices. Some results reported by Voules Group, Science and Technology at the Atomic. Scale, Spin-

tronics Materials and Devices, have been reproduced in **Figure 2**.

It can be observed that as expected on the basis of theory, EELS of the Fe_3-xTixO_4 layer, and EELS of the Fe_3O_4 layer, though quantitatively different are qualitatively similar. The difference in values is due to the difference in their structure, and the qualitative similarity is due to their similar nature of influence. It may also be noted that EELS can be utilized to obtain both magnetic linear and circular dichroic signals from ferromagnetic and paramagnetic materials for experimentally evaluating the origin of magnetization in complex magnetic materials.

4. Conclusion

Most suitable material has to be carefully chosen for the particular device. The coating Technology commonly employed for Epitaxial growth for smooth layer by layer structure is vapor-phase epitaxy (VPE) for Epitaxial silicon, which is a modification of chemical vapor deposition. Molecular-beam and liquid-phase epitaxy (MBE and LPE) are also used, mainly for compound semiconductors. Solid-phase epitaxy is used primarily for crystal-damage healing. For obtaining uniformity and also for negligible scattering in the coatings, Dual Ion beam



(a)

(b)

Figure 2. (a) Fe_3O_4/Fe interface (left), Fe_3-xTixO_4 at the Fe/TiN interface (right), (b) EELS of the Fe_3O_4 layer (left), and EELS of the Fe_3-xTixO_4 layer (right),Figure courtesy Voules Group, Science and Technology at the Atomic. Scale, Spintronics Materials and Devices.

sputtering (DIBS) Unit is required, for which various process Parameters like rate of deposition, gaseous flow and degree of vacuum have to be optimized for achieving efficient and reproducible results.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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