Spintronics – Theoretical Analysis and Designing of Devices Based on Giant Magnetoresistance

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Foreword

It is a matter of great pleasure for me to express that Dr Kamal Nain Chopra, has made a tremendous and commendable effort in writing this monograph on the topic–Spintronics-Theoretical Analysis and Designing of Devices based on Giant Magetoresistance, on which the availability of literature, especially at one place, is the need of the hour for the DRDO scientists in particular, and the researchers and academicians in general. Theoretical analysis of nearly all types of devices in this category have been discussed in detail in this monograph, thereby making it very useful indeed for the scientific community both in India and abroad. Prior to this, very few attempts seem to have been made in presenting the different aspects of the subject at one place, and therefore, this effort will certainly bridge the gaps between the various types of research papers and literature on various novel aspects of this fascinating field. An important feature of this monograph is that the recent research important studies in the field have been presented and technically analysed. The monograph should especially be useful for the designers and engineers of Spintronics Devices, as the design aspects for the efficiency optimisation have been presented and discussed at length. In addition, the monograph is expected to be of immense utility for the budding researchers and scientists in the field, since it provides a large number of theoretical and experimental results available in the literature for them to have a clear understanding of the subject, and also to choose the direction in which to move for carrying out research in this novel field. It is my sincere wish that this monograpdh serves the researchers in enhancing their inputs on the subject, and also their interest in making more concentrated efforts in carrying out research in this rapidly evolving field.

Prof (Dr) Vipin Kumar Tripathi
Optoelectronics and Plasmas Group, Department of Physics
Indian Institute of Technology, Delhi

Preface

Spintronics, or spin electronics, is based on the controlling and manipulating the spin degrees of freedom in solid-state systems. This monograph is the culmination of the Thought Process started in the mind of the author, during his association with Research Team in the Department of Physics, Indian Institute of Technology, Delhi, as a Research Scientist in the year 2010. It discusses the present status of the subject regarding the progress in the techniques, applications and the results of some recent researchers. The basic principles of the generation of carrier spin polarization, spin dynamics, and spin-polarized transport have been discussed. It is important to note that the spin transport is basically different from the charge transport, as the spin in solids is dependent on the spin-orbit and hyperfine coupling, and thus is a nonconserved quantity. This interesting subject has been introduced in detail.

Spintronics as Spin-based Electronics, Main issues in Semiconductor Spintronics, Magnetic Semiconductors, Diluted Magnetic Semiconductors (DMSs), and Alloys of a Nonmagnetic Semiconductor have been discussed briefly. Effect of the Application of a Magnetic Field on the Energy Degeneracy and Measurement of the Magnetic State of a Thin Epilayer have been explained. The topics like 'Spinning electrons' in semiconductor components, Advantages of the Property of Spin for Spintronic Devices, and some Concepts connected with Spintronics have been dealt with for bringing clarity to the readers. The concepts discussed include Spin Transfer, Spin Transfer Torque, Spin-pumping Force and Spin Currents, Tunneling Anisotropic Magnetoresistance, and Tunnel Magnetoresistance in Semiconductor Magnetic Tunnel Junction, Spin-dependent Magnetoresistance in all-semiconductor Heterostructure, and Magnetic Induced and Current Induced Switching. Some fundamental studies like Magnetic Tunneling Junctions, their types, and structures have been included in the text. The evolution of this interesting field has been brought out explicitly. A review of the recent experimental results of the researchers has been presented to apprise the readers with the likely applications. Some new functions not possible with the conventional electronics and possible in spintronics have been described, which are based on using external electric and magnetic fields, and in some cases by illuminating with light. Applications of Spintronics in various fields including Research and Quantum Computers, and the fabrication of the Spintronics devices have also been described at length. Materials Selection for the Device Fabrication, results of the experimental studies useful for the designing of the materials with custom made characteristics required for the spintronics devices, and some Important Experimental Breakthroughs useful for Spintronics have been presented very briefly for the benefit of the designers and the researchers, which can help them to read the required papers and develop the understanding of the topics of their interest.

Spintronics is a new and emerging field, which can be considered as an offshoot of electronics. It is based on the spin of electrons for the flow of current, and not on the movement of electrons, which is the case with electronics. So, in a way, the dawn of spintronics has resulted in a slight modification of the definition of current, in that it can be present even in the absence of the flow of the electrons, if there is a change in the spin of the electrons. Current Research, Recent Trends, and Concluding Remarks about the subject have also been described for getting the latest insight into the field. Technical Terms and the List of Acronyms used in the field of Spintronics have been given at the end of the monograph to acquaint the reader with Terminology.

Spintronics is developing at a very fast pace, and it should not be surprising if this field competes with electronics and even takes a lead in the near future, especially in the applications of storage devices and quantum computation. It is felt that this topic should be incorporated in the syllabus of B Tech (Electronics), as a first step which will pave the way for the award of a full-fledged degree course in the field of 'Spintronics' in the future, by some university. The premier institutes like IISc, Bangalore and IITs can take the initiative in this direction. The present Monograph is an effort made in the direction of giving a fillip to the research activity in this emerging field, and aims to help the researchers in understanding the (i) Design aspects of the spintronics based devices for the optimized performance of these devices by maximizing their efficiency, and (ii) technicalities of the experimental investigations given in the literature. Thus, it is hoped that the monograph should be useful to the new entrants in the field, and also the engineers and designers engaged in the development of the spintronics based devices.

Delhi KN Chopra

Acknowledgements

The author is really grateful to DRDO in general, and LASTEC in particular for providing an opportunity to work for many years with a number of scientists working on Optoelectronic devices, including lasers and Thin Films Coating Techniques , and the systems based on lasers. My sincere thanks are due to Dr Rambabu, Director, RCI, Hyderabad, and Shri G Krishna Rao, Director, Electro-Optical Instruments Research Academy (ELOIRA), Hyderabad, for giving me opportunities to give invited Talks, and attend Review meetings on Laser Coatings and Ring Laser Gyroscopes, thereby providing me the chances to interact with the scientists of DRDO laboratories of Hyderabad, and also academicians of the Indian Institute of Science, Bangalore, the discussions with whom helped me in the final refinements of the monograph. Thanks are also due to Dr MN Reddy, Scientist G, LASTEC, and Dr C Natrajan, Scientist G, DGECS, DRDO, Bangalore, for the important discussions with them, which helped me in giving final touches to this interesting field. Finally, the author is grateful to Prof Vipin Kumar Tripathi of the Optoelectronics and Plasmas Group of the Department of Physics, Indian Institute of Technology, Delhi, for various suggestions and encouragement during the course of writing this monograph, which helped me in greatly improving the contents and more importantly the presentation and readability of the monograph. The author is also thankful to two anonymous reviewers of the monograph, for their encouraging and valuable comments, which helped me in improving the contents of the Monograph.

Finally, the author sincerely thanks Director, DESIDOC, Ms Alka Bansal and Ms Kavita Narwal for their continuous support and cooperation, without which it would not have been possible to present the monograph in the present form.

Dr KN Chopra

List of Acronyms

AC	Alternating Current
AHE	Anomalous Hall Effect
AMR	Anisotropy Magnetoresistance
CIS	Current-Induced Switching
CMOS	Complementary Metal-Oxide-Semiconductor
CMR	Colossal Magnetoresistance
DBR	Distributed Bragg Reflector
DC	Direct Current
DFT	Density Functional Theory
DMS	Dilute Magnetic Semiconductor
DRAM	Dynamic Random Access Memory
EB	Electron Beam
EPR	Electron Paramagnetic Resonance
EXAFS	Extended X-ray Absorption Fine Structure
FET	Field Effect Transistor
FMR	Ferro-Magnetic Resonance
FRITD	Ferromagnetic Resonant Interband Tunneling Diode
GMR	Giant Magnetoresistance
GMR-STO	Giant Magnetresistance-based Spin Torque Oscillator
GNR	Graphene Nano-Ribbons
HDD	Hard Disk Drive
IMEC	Interuniversity Micro-Electronics Centre
ITRS	International Technology Roadmap for Semiconductors
LED	Light Emitting Diode
MBE	Molecular Beam Epitaxy
MFT	Master File Table
MIG	Metal In Gap
MIS	Magnetic-Induced Switching

MOKE	Magneto-Optical Kerr Effect
MQCA	Magnetic Quantum Cellular Automata
MR	Magnetoresistance
MRAM	Magnetoresistive Random Access Memory
MRFM	Magnetic Resonance Force Microscope
MTJ	Magnetic Tunneling Junction
PLD	Pulsed Laser Deposition
PMTJ	Perpendicular Magnetic Tunnel Junction
PTB	Physikalisch-Technische Bundesanstalt
QW	Quantum Well
RHEED	Reflection High-Energy Electron Diffraction
SAF	Synthetic Anti-Ferromagnet
SDF	Spin Density Functional
Spin FETs	Spin Field Effect Transistors
SFQ	Single Flux Quantum
SMT	Spin Momentum Transfer
SQUID	Superconducting Quantum Interference Device
SRAM	Static Random Access Memory
ST	Spin Transfer
STO	Spin Torque Oscillator
STT	Spin Transfer Torque
STT-RAM	Spin Transfer Torque Random Access Memory
STT-MRAM	Spin Transfer Torque-Magnetoresistive Random Access Memory
SV	Spin-Valve
SVT	Spin-Valve Transistor
TAS	Thermal Assisted Switching
TEM	Transmission Electron Microscopy
TGFs	Triangular Graphene Nano-Flakes
TIs	Topological Insulators
TMR	Tunneling Magnetoresistance
TP-STO	Tilted-Polariser Spin Torque Oscillator
VCMA	Voltage Controlled Magnetic Anisotropy
VMRAM	Vertical Transport MRAM

CHAPTER 1

Introduction to Spintronics

1.1 INTRODUCTION

Spintronics is a new branch of electronics in which electron spin, in addition to charge, is manipulated to yield a desired electronic outcome. All spintronic devices act according to the simple scheme: (i) information is stored (written) into spins as a particular spin orientation (up or down), (ii) the spins, being attached to mobile electrons, carry the information along a wire, and (iii) the information is read at a terminal. Spin orientation of conduction electrons survives for a relatively long time (nanoseconds, compared to tens of femtoseconds during which electron undergoes momentum and energy decay), which makes spintronic devices particularly attractive for memory storage and magnetic sensors applications, and, potentially for quantum computing where electron spin would represent a bit (called qubit) of information.

It is clear that the field of spintronics is based upon the use of the direction of spin of electrons rather than their charge (positive or negative). Spin-polarised electrons can be considered to have two states; spin-up or spin-down, which can be used to represent on and off state, respectively. It is important to note that most of the successful researches in this field have only been at very low temperatures. In the conventional semiconductors, the usage of electron is in a purely binary proposition, i.e., electron's state represents only 0 or 1, and a set of eight bits can represent every number (though singly) between 0 and 255. Spintronics makes use of quantum bits, called qubits which exploit the 'spin up' and 'spin down' states as superpositions of 0 or 1, and also possesses the ability to represent every number between 0 and 255 simultaneously.

1.2 CONCEPTS OF SPINTRONICS AND ITS APPLICATIONS

It is interesting to note that all the magnetoelectronic devices like memory elements, read heads, and industrial sensors make use of the unique properties of magnetic materials. Their working is based on the Magnetoresistance (MR) effect, which is dependent on the relative orientation of the magnetisation in the magnetic layers. These devices utilise the device resistance changes from small values for parallel magnetisations to very large values for anti-parallel magnetisations, to sense changes in magnetic fields. Since, the electron's magnetic momentum is proportional to its spin, spintronics is intrinsically linked to magnetism. This change in resistance is used to sense changes in magnetic fields. Concepts of spintronics can be understood on the basis of Fig. 1.1.

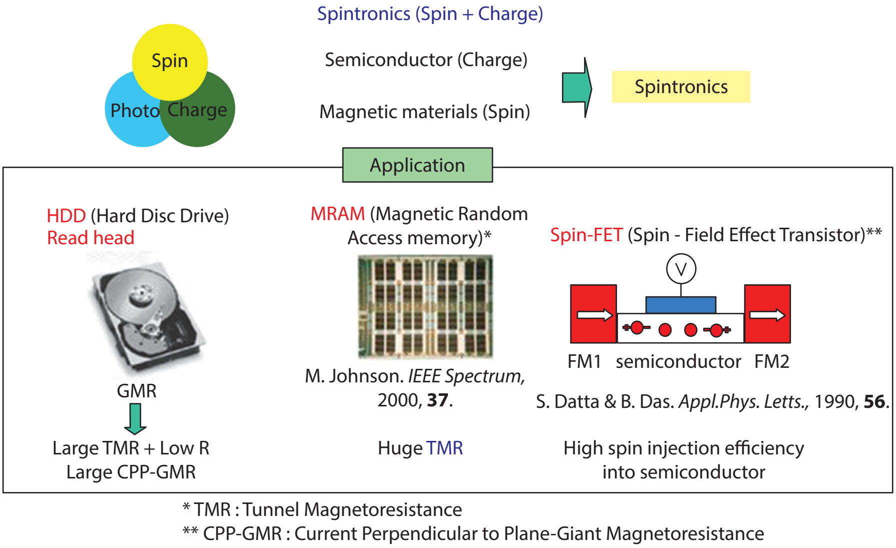

Figure 1.1. Concept of spintronics and some of its applications.

Source: Johnson[1], M. *Spectrum* and Datta[2], S. & Das B., *Appl. Phys. Letts.*

A spin polarised current can be generated in a very simple way by passing the current through a ferroelectric material. However, this can work only if the ferroelectric is in the form of a single crystal, as only such a crystal filters the electrons uniformly. It is interesting to know that one can also make a spin sensitive detector by putting a ferroelectric filter in front of a simple device like, transistor. It is clear that a current is passed in case the two magnetic fields are aligned (i.e., parallel). In case of an opposed spin state, i.e., anti-parallel, there is no passage of current because the resistance of the whole system is very much higher.

The most important application of spintronics is in the field of mass storage devices. It is very satisfying to note that just after the dawn of this century – in 2002, IBM scientists succeeded in compressing massive amounts of data into a small area ~ one trillion bits per square inch. With the advent of spintronics, it has become possible to double the bandwidth of the cable. This is achieved by putting a pair of signals in a single wire, by using spin-polarised electrons and producing different signals for spin-up electrons and spin-down electrons. There are also some radical devices that have a unit in between these states that does some processing to the current of electrons, dependent on the spin states.

One of the most successful spintronic devices is the spin value, which utilises a layered structure of magnetic materials, and has the ability of displaying a large sensitivity to magnetic fields. This is based on the principle that it allows all the electrons through in the presence of a magnetic field, but few with some spins in the absence of such a field. Because of its sensitivity to very weak fields, it is widely used as the transducer in computer hard disk drive heads since the dawn of this century. It is considered that this technology of 'Spintronics' will lead to devices that consume massively less power than traditional electronics. One of the most important breakthroughs reported in the Journal *Nature*, is that the researchers have been able to manipulate and detect the quantum mechanical state of spin-polarised electrons in silicon even at room temperature. The added attraction of this observation is that silicon is already widely used in existing chip fabrication processes. The possibility of altering and reading the state at room temperature has a great potential, as any future mass-market spintronic devices would need to operate at room temperature. The spintronic devices are of tremendous use in the silicon-based chips, because of the fact that they consume very less power, and also generate less heat.

Spintronic devices are particularly attractive for memory storage and magnetic sensor applications, and also have potential for quantum computing. Difficult materials challenges must be overcome to fabricate a semiconductor-based electronic device where the spin controls the characteristics. When combining magnetic materials with semiconductors in a single device, it is important to create a close contact. Another challenge is the spin-injection, or the creation of a spin packet in the semiconductor. 'Quantum computation' is one of the most ambitious applications of the electron spin, in which, the spins are dealt with as a very promising quantum effect. The spins of the electrons are expected to play an important role in the quantum computers, as they can be used as qubits or quantum bits. However, the research in this direction is in its early days.

1.3 SPINNING ELECTRONS IN SEMICONDUCTOR COMPONENTS

The electron has an intrinsic angular momentum with a spin valve equal to half, which can be either spin-up or spin-down. In case of standard electronic devices, the electric current consists of equal numbers of spin-up and spin-down electrons. Electronic devices can be made to function on the spin of the carriers rather than on the charge, by disturbing this equality of the numbers of spin-up

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About the Book

In this monograph, the basic principles of the generation of carrier spin polarisation, spin dynamics, and spin-polarised transport have been discussed. Spintronics as spin-based electronics, main issues in semiconductor spintronics, magnetic semiconductors, diluted magnetic semiconductors and alloys of a nonmagnetic semiconductor have been discussed briefly. The topics like 'spinning electrons' in semiconductor components, advantages of the property of spin for spintronic devices, and some concepts connected with spintronics have been dealt with for bringing clarity to the readers. A review of the recent experimental results of the researchers has been presented to apprise the readers with the likely applications. Various concepts discussed include spin transfer, spin transfer torque, spin-pumping force and spin currents, tunneling anisotropic magnetoresistance, and tunnel magnetoresistance in semiconductor magnetic tunnel junction, spin-dependent magnetoresistance in all-semiconductor heterostructure, and magnetic induced and current induced switching. Some fundamental studies like magnetic tunneling junctions, their types, and structures have been included. Some new functions not possible with the conventional electronics and possible in spintronics have been described. Applications of spintronics in various fields including research and quantum computers, and the fabrication of the spintronics devices have also been described at length. Materials selection for the device fabrication, results of the experimental studies useful for the designing of the materials with custom made characteristics required for the spintronics devices, and some important experimental breakthroughs useful for spintronics have been presented very briefly for the benefit of the designers the researchers and the academicians, which can help them to develop the understanding of the topics of their interest.

About the Author

Dr Kamal Nain Chopra has done BSc (University of Delhi), MSc (Physics - IIT, Delhi), MTech (Opto-Electronics - IIT, Delhi), and PhD (Applied Physics - IIT, Delhi). He has served DRDO for a period of 33 years and superannuated as Scientist G, from Laser Science and Technology Centre (LASTEC), Delhi, in the year 2005. Subsequently, he has also served as Professor (Physics) in NSIT, University of Delhi, and as Project Scientist in IIT, Delhi, in various Projects, on Topics including Photonics and Spintronics.

He has about 375 publications including 285 in International journals on various topics including Thin Films Optics, Lasers and Lasesr Components, Holography, and Modern Optics; 12 invited talks; 14 Technical reports; and 24 papers in Conference Proceedings.

He has co-authored three books titled, "Thin Films and their Applications in Military and Civil Sectors", 2010; 'Unconventional Lasers: Design and Technical Analysis', 2017, both published by DESIDOC, DRDO, Ministry of Defence, India; and 'Conventional and Unconventional Sources of Renewable Energy: Renewable Energy Sources", 2017, Lambert Academic Publishing, LAP, Germany.

He has undertaken visits to foreign universities and industries including: School of Thin Film Coatings, Department of Physics, St Jerome University, Marseille, France (1984-85); Department of Physics, Innsbruck University, Austria; M/s Balzers, Liechtenstein, Switzerland (1995); and M/s Elettrorava, Torino, Italy (2000).
He has vast experience of serving the Recruitment and Assessment Boards of DRDO (RAC and CEPTAM), as Chairman as well as Expert Board Member.

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