

Effect of Interlayer Coupling and Biasing on Spin Transfer Torque Switching in Ferromagnetic Nanopillars

*A thesis submitted to Bharathidasan University
for the award of the degree of*

DOCTOR OF PHILOSOPHY
in
PHYSICS

by

D. ARAVINTHAN

[Reg. No.: 34151/Ph.D.1/Physics/Full-Time/October 2011/Date: 21.11.2011]

Under the supervision of

Prof. M. DANIEL



Centre for Nonlinear Dynamics
School of Physics
Bharathidasan University
Tiruchirappalli - 620 024
Tamilnadu, India

SEPTEMBER 2016



**CENTRE FOR NONLINEAR DYNAMICS
SCHOOL OF PHYSICS
BHARATHIDASAN UNIVERSITY
TIRUCHIRAPPALLI - 620 024
TAMILNADU, INDIA**

**Dr. M. Daniel
Professor (Retd.)**

CERTIFICATE

Certified that the work reported in this thesis entitled “**Effect of Interlayer Coupling and Biasing on Spin Transfer Torque Switching in Ferromagnetic Nanopillars**” is based on the bonafide work done by **Mr. D. Aravinthan** under my guidance in the Centre for Nonlinear Dynamics, School of Physics, Bharathidasan University, Tiruchirappalli - 620 024, during the period 2011-2016 and has not been included in any other thesis submitted previously for the award of any degree.

**TIRUCHIRAPPALLI - 620 024
SEPTEMBER 2016**

**[M. DANIEL]
SUPERVISOR**



CENTRE FOR NONLINEAR DYNAMICS
SCHOOL OF PHYSICS
BHARATHIDASAN UNIVERSITY
TIRUCHIRAPPALLI - 620 024
TAMILNADU, INDIA

DECLARATION

Declared that the work presented in this thesis is based on the original work done by me under the guidance of **Dr. M. DANIEL**, Professor (Retd.), Centre for Nonlinear Dynamics, School of Physics, Bharathidasan University, Tiruchirappalli - 620 024, during the period 2011-2016 and has not been included in any other thesis submitted previously for the award of any degree.

TIRUCHIRAPPALLI - 620 024
SEPTEMBER 2016

[D. Aravinthan]

To everyone who shared an important path in my journey to this point.

PREFACE

Exciting developments in magnetic materials research started with the computer revolution in the late 1950s and the more recent quantum leap beginning around 1990 associated with the electron's quantum property-spin based electronics or simply *Spintronics*. The field of spintronics was largely triggered with both Albert Fert's and Peter Grünberg's independent and simultaneous pioneering discovery of Giant Magnetoresistance (GMR) in 1988. Another breakthrough in spintronics came from both Slonczewski's and Berger's independent prediction of *Spin transfer torque* in 1996. The spin transfer torque arises due to an exchange interaction and angular momentum transfer between the injected spin polarized 'itinerant' electrons and the local moments in the ferromagnet, when the current passes through the ultrathin ferromagnetic films separated by a non-magnetic metal. This spin transfer torque will switch the magnetization of the free layer in the multilayer nanopillar structure for a sufficiently large current. Spin transfer torque induced magnetization switching has recently attracted much interest due to its potential applications in magnetic random access memory (MRAM), fast programmable logic, high-density magnetic storage devices, magnetic sensors and in high frequency devices for telecommunications. Magnetic storage devices and magnetic sensors based on GMR and Tunnelling Magnetoresistance (TMR) effects require high quality multilayers constructed out of ultrathin ferromagnetic and non-magnetic films. The performance of these devices strongly depend on the morphological and structural properties of the films and their physical characteristics. Among them, the crucial factor is the interlayer coupling between the two ferromagnetic layers separated by a non-magnetic spacer. Various interlayer coupling mechanisms have been reported. Among them, pinhole coupling, orange peel coupling, biquadratic coupling and RKKY

coupling are important ones. These interlayer couplings play an important role in the understanding of magnetization switching mechanism and GMR of spin valves and TMR of magnetic tunnel junction structures.

The main objective of this work is to understand the physics of various couplings especially orange peel coupling and biquadratic coupling and their effect on the spin transfer torque induced magnetization switching. Further, the reduction of critical current density and switching time are two important issues in the development of potential applications. In order to reduce the switching time, the effect of biasing on spin transfer torque switching in the pentalayer nanopillar structure is additionally studied. The magnetization dynamics and the switching process of the free layer magnetization in nanopillar devices are basically nonlinear in nature and is governed by the Landau-Lifshitz-Gilbert-Slonczewski (LLGS) equation which is a highly nontrivial vector nonlinear evolution equation. By solving this LLGS equation, we can understand the underlying magnetization dynamics. But, it can not be solved analytically in the more general case due to its high nonlinear nature. In the time-independent case, the LLGS equation is analytically solved to calculate the critical current density required to switch the magnetization. Then the full LLGS equation is solved numerically by using Runge-Kutta fourth order procedure in each case and from the numerical results we understand the effect of the interlayer coupling and biasing on spin transfer torque switching.

The contents of thesis is divided into seven chapters in four parts. The first two chapters forms the introductory part (Part I) which provide the basis for our investigations. In Chapter 1, a brief introduction and an overview of the magnetization switching process, details about various methods available to achieve magnetization switching and important magnetoresistance effects are presented. The dynamics of magnetization switching can be understood from constructing appropriate model and the

dynamical equation and the switching process can be understood from by solving the equation. In Chapter 2, dynamical equation for magnetization switching process is constructed.

The results of the investigations on the effect of interlayer coupling on spin transfer torque switching in trilayer structure are presented in chapters 3 and 4 under Part II. In Chapter 3, the impact of orange peel coupling on spin torque magnetization switching in a trilayer nanopillar device is investigated by solving the switching dynamics of magnetization of the free layer governed by the LLGS equation. Chapter 4, concentrates on the study of the effect of biquadratic coupling on spin torque switching in a trilayer nanopillar structure.

Part III containing chapters 5 and 6 describes the results of our study on the magnetization switching dynamics in a pentalayer nanopillar structure. Chapter 5 deals in a greater detail with the numerical results about the role of interlayer coupling (both orange peel coupling and biquadratic coupling) on the magnetization switching in the pentalayer nanopillar. Chapter 6 is devoted to the investigations on the effect of biasing for reducing the switching time in the pentalayer structure.

Part IV consists of Chapter 7, which provides the summary and conclusions of our investigations carried out in this thesis and the future outlook.

Tiruchirappalli

September 2016

D. Aravinthan

Acknowledgements

“A timely benefit, -though thing of little worth,
The gift itself, -in excellence transcends the earth.”

- Thirukkural (102)

It has been an incredible journey that brought me to the completion of this dissertation. I am deeply indebted to everyone who shared an important path in my journey to this point. It is their support and inspiration that made this adventure both pleasant and fruitful.

First and foremost, I thank my research supervisor Prof. M. Daniel for giving freedom, guidance and support. I admire the way he approaches the research problem from both physical and mathematical point of view. Also, I am amazed about his planning, punctuality, positive attitude and patiently correcting and offering suggestions on anything, whether it is a letter or manuscript or thesis (including this one!). Throughout the years, I have learned a lot from him on both professional and personal level. Thank You Sir!

I am forever thankful to my collaborator and my senior Dr. P. Sabareesan, Assistant Professor, SASTRA University, Thanjavur for being with me throughout my research work. I extend my thanks for his moral support, enthusiastic words, guidance and advice filled with care. Thank You Anna!

It is a great pleasure to thank my co-guide Dr. M. Senthilvelan, Assistant Professor, Centre for Nonlinear Dynamics, Bharathidasan University for his constant support and advice. I wonder about his obsession with Mathematics.

I am very much thankful to my doctoral committee member Prof. K. Thamilmaran, Head, Centre for Nonlinear Dynamics, Bharathidasan University for periodically appraising the progress of my research work. I extend my thanks for his continuous help, support and kind words.

Also, I am happy to thank the other doctoral committee member Prof. S. Rajasekar, Head & Chair, School of Physics, Bharathidasan University for periodically monitoring the progress of my research work and asking critical and interesting questions which challenges me to dig deeper.

I am grateful to Prof. M. Lakshmanan, Professor of Eminence & NASI Senior Scientist, Centre for Nonlinear Dynamics, Bharathidasan University for his support, encouragement and insightful questions that motivated me to learn more.

It is my great pleasure to thank Prof. S. Dhanuskodi, Prof. S. Arumugam, Prof. K. Jeganathan, Dr. P. Muruganandam, Dr. R. Ramesh Babu, Dr. T. C. Sabari Girisun and Dr. L.C. Nehru, Faculty Members, School of Physics, Bharathidasan University for their support, questions and comments during the doctoral research committee meetings and the departmental seminars.

I extend my thanks to Dr. B. Jeyapragash and Dr. M. Surulinathi, Faculty Members, Department of Library and Information Science, Bharathidasan University for their help, support and constant encouragement.

I thank my research group members Dr. M. Vanitha, Dr. A. Arul Gnanam, Mr. R. Arun, Mr. D. Giridharan and Mr. K. Prabakaran for the fruitful discussions and their help & support.

My special thanks to my friend Mr. P. A. Praveen, Research Scholar, School of Physics, Bharathidasan University for illustrations of our models in this thesis and for many interesting discussions on a wide range of topics ranging from latex to latest literature books.

I express my sincere thanks to Dr. R. Jothimurugan and Mr. K. Suresh for their assistance in numerical programming & computer, Mr. S. Stalin for his help in analytical calculations, and Mr. N. Ananth and Mr. T. Sri-raman for their technical support. Apart from the academic support, each one helped me in many ways and gave their continuous support and encouragement. I extend my thanks to Ms. R. Parameshwari for her help in the procedure of INSPIRE Fellowship procedure from scratch till end and her encouraging words.

I am grateful in acknowledging the Department of Science and Technology (DST), Govt. of India for the financial support in the form of DST-INSPIRE Fellowship. It is one of the motivating factors to join for Ph.D.

I extend my thanks to the organizers of 2016 - Joint MMM-Intermag Conference held at the Hilton San Diego Bayfront Hotel in San Diego, California, United States for providing a Student Travel Grant for participating in the Conference.

I wish to thank the University Library and University Informatics Centre authorities for providing the wonderful learning facilities.

I express my thanks to Mrs. S. Sumathi and all the non-teaching staff members of the School of Physics and Administrative Office, Bharathidasan University for their support in the administrative process.

I thank the Management of Dr. SNS Rajalakshmi College of Arts and Science (Autonomous), Coimbatore for providing facilities during the writing of my thesis.

My friends and classmates have been a continuous fountain of support and companionship. I thank Mr. K. Manikandan, Mr. M. Vadivel, Dr. S. Sadhasivam, Mr. S. Raja, Mr. M. Gopalakrishnan, Mr. S. Sabarathinam and Mr. C. Murugesan for their care, help, support and being with me throughout the period of my Ph.D. Work.

I wish to thank my fellow scholars in our department, Dr. Ajey Kumar Tiwari, Dr. S. P. Prabakaran, Dr. R. Mohandoss, Dr. D. Mohan Radheep, Dr. S. Esakkimuthu, Dr. M. Kanagaraj, Dr. R. Suresh, Dr. V. Chithika Ruby, Dr. R. Durga Devi, Dr. P. S. Swathy, Dr. U. Devarajan, Mr. B. Subash, Mr. R. Gopal, Ms. S. Amreetha, Ms. P. Rajeshwari, Sr. Nisha Francis, Mr. K. Karthik, Mr. P. Senthilkumar, Mr. K. Manikandan, Mr. M. Manikandan, Mrs. P. V. Bhuvanewari, Mrs. T. Indira Gandhi, Mr. M. Sukumar, Mr. P. Velusamy, Mr. K. Arjunan, Mr. P. Mega Varna Ezhilarasu, Mr. S. Leo Kingston, Mr. D. Premraj, Mrs. K. Abirami, Ms. S. Rajamani, Mrs. L. Mohanasubha, Ms. S. Karthiga, Ms. K. Premalatha, Ms. S. Bhuvanewari, Mr. R. Ravishankar, Mr. P. Justin Jesuraj, Mr. V. Rajiv, Mr. P. Dharmaraj, Mr. S. Gopalakrishnan, Mr. N. Anbarasan, Mr. K. Manikandan, Mr. C. Saravanan, Mr. C. Jeganathan, Mr. M. Saravanan, Ms. N. Priyadarshani and Mr. R. Bharthasaradhi for their support and making the period of my Ph.D. an enjoyable one.

During my time at Bharathidasan University, I have had the opportunity to make a number of good friends, and I wish to thank them all for the many hours of fun, I had enjoyed with them. These people include Dr. V. Ramalingam, Mr. D. Chellapillai, Mr. R. Thiyagu, Mr. Abhishek Raj, Dr. S. Ananth, Mr. N. Annamalai, Mr. S. Anbalagan, Mr. D. Mahamuni, Mr. A. Murugadas, Mr. B. S. Karthikeyan, Mr. A. William James, Mr. R. Vijayakumar, Mr. K. Varunkumar, Mr. S. Sampathkumar, Dr. C.

Sivaprakasam, Mr. R. Ramachandran and Dr. C. R. G. Siva.

Also, I thank my friends Mr. E. Siva, Dr. C. Jeevarathinam, Mr. S. Udhayakumar, Ms. A. Bhuvaneshwari, Ms. S. Mathuri, Mrs. G. Ponmalar, Mr. G. Kalaiselvan, Mr. J. B. Sudharshan, Mr. P. Sakthivinayagam, Mr. D. Felix Irudhayaraj, Mr. S. Senthilkumar, Mr. R. Rajeshwaran, Mr. H. Bhoomeswaran, Ms. R. Sangeetha Devi and Ms. S. Latha for their support and encouragement.

I am deeply grateful to my wonderful roommates Mr. J. Sivakumar, Mr. T. Mathimani, Mr. K. Boopathi, Mr. R. G. Bharadvaj, Dr. M. Logeshwaran, Dr. M. Ayyanar, Mr. S. L. Dinesh and Mr. S. Rakesh for making my hostel days pleasant and memorable one.

I thank Mr. N. Prakash and Mr. C. Puravi for their hospitality during my academic visits to Chennai and their kind help. I extend my thanks to Mr. P. Prabakaran for his help, support and continuous encouragement.

I am deeply indebted to my father Mr. P. Devarasu, my mother Mrs. D. Vijayalakshmi, my aunt Mrs. T. Logambal and my dear brothers Mr. D. Dineskumar & Mr. P. Senthilkumar for their unconditional love, care, unfailing support and being with me throughout my journey.

Finally, I thank the people of my village (Iluppaiyur) for their affection and support in all possible ways.

Over the years, I have learned an incredible amount from all of you. Thank You All!

Tiruchirappalli

September 2016

D. Aravinthan

List of Publications

1. **D. Aravinthan**, P. Sabareesan, and M. Daniel, *Current induced magnetization switching in Co/Cu/Ni-Fe nanopillar with orange peel coupling*, AIP Advances, **5**, 077166, (2015).
2. **D. Aravinthan**, P. Sabareesan, and M. Daniel, *Impact of biquadratic coupling on critical current density in Co/Cu/Ni-Fe nanopillar*, AIP Conf. Proc., **1728**, 020443, (2016).
3. **D. Aravinthan**, P. Sabareesan, and M. Daniel, *Effect of biquadratic coupling on current induced magnetization switching in Co/Cu/Ni-Fe nanopillar*, AIP Conf. Proc., **1731**, 130032, (2016).
4. **D. Aravinthan**, P. Sabareesan, and M. Daniel, *Reduction of switching time in pentalayer nanopillar device with different biasing configurations*, J. Magn. Magn. Mater., **421**, 409, (2017).
5. **D. Aravinthan**, P. Sabareesan, and M. Daniel, *Spin transfer torque switching in pentalayer nanopillar with biquadratic coupling*, (Manuscript submitted to J. Magn. Magn. Mater.).
6. **D. Aravinthan**, P. Sabareesan, and M. Daniel, *On the effect of orange peel coupling on spin torque magnetization switching in pentalayer nanopillar*, (To be submitted).

Contents

Preface	iv
Acknowledgements	vii
List of Publications	xi
List of Abbreviations	xv
List of Symbols	xvi
Part I : Background & Motivation	1
1 First Chapter of the Thesis	2
1.1 First Section	2
1.1.1 Test Subsection	2
1.2 conclusion	3
2 Chapter Title Here	4
2.1 Main Section 1	4
2.1.1 Subsection 1	4
2.1.2 Subsection 2	4
2.2 Main Section 2	5
2.3 conclusion	6
Bibliography	7
Publications	8

List of Figures

2.1 Electron model	5
------------------------------	---

List of Tables

List of Abbreviations

AMR	Anisotropic Magnetoresistance
GMR	Giant Magnetoresistance
LLGS	Landau-Lifshitz-Gilbert-Slonczewski
MRAM	Magnetic Random Access Memory
RK4	Runge-Kutta Fourth Order

List of Symbols

Name	Symbol
Amplitude of the interface waviness	A
Angular momentum	L
Applied current density	J
Critical current density	J_c

Part I

Background & Motivation

Chapter 1

First Chapter of the Thesis

1.1 First Section

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

1.1.1 Test Subsection

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

1.2 conclusion

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

Chapter 2

Chapter Title Here

2.1 Main Section 1

Lorem ipsum dolor sit amet, consectetur adipiscing elit. Aliquam ultricies lacinia euismod. Nam tempus risus in dolor rhoncus in interdum enim tincidunt. Donec vel nunc neque. In condimentum ullamcorper quam non consequat. Fusce sagittis tempor feugiat. Fusce magna erat, molestie eu convallis ut, tempus sed arcu. Quisque molestie, ante a tincidunt ullamcorper, sapien enim dignissim lacus, in semper nibh erat lobortis purus. Integer dapibus ligula ac risus convallis pellentesque.

2.1.1 Subsection 1

Nunc posuere quam at lectus tristique eu ultrices augue venenatis. Vestibulum ante ipsum primis in faucibus orci luctus et ultrices posuere cubilia Curae; Aliquam erat volutpat. Vivamus sodales tortor eget quam adipiscing in vulputate ante ullamcorper. Sed eros ante, lacinia et sollicitudin et, aliquam sit amet augue. In hac habitasse platea dictumst.

2.1.2 Subsection 2

Morbi rutrum odio eget arcu adipiscing sodales. Aenean et purus a est pulvinar pellentesque. Cras in elit neque, quis varius elit. Phasellus fringilla, nibh eu tempus venenatis, dolor elit posuere quam, quis adipiscing urna leo nec orci. Sed nec nulla auctor odio aliquet consequat. Ut nec nulla

in ante ullamcorper aliquam at sed dolor. Phasellus fermentum magna in augue gravida cursus. Cras sed pretium lorem. Pellentesque eget ornare odio. Proin accumsan, massa viverra cursus pharetra, ipsum nisi lobortis velit, a malesuada dolor lorem eu neque.



FIGURE 2.1: Electron model

2.2 Main Section 2

Sed ullamcorper quam eu nisl interdum at interdum enim egestas. Aliquam placerat justo sed lectus lobortis ut porta nisl porttitor. Vestibulum mi dolor, lacinia molestie gravida at, tempus vitae ligula. Donec eget quam sapien, in viverra eros. Donec pellentesque justo a massa fringilla non vestibulum metus vestibulum. Vestibulum in orci quis felis tempor lacinia. Vivamus ornare ultrices facilisis. Ut hendrerit volutpat vulputate. Morbi condimentum venenatis augue, id porta ipsum vulputate in. Curabitur luctus tempus justo. Vestibulum risus lectus, adipiscing nec condimentum quis, condimentum nec nisl. Aliquam dictum sagittis velit

sed iaculis. Morbi tristique augue sit amet nulla pulvinar id facilisis ligula mollis. Nam elit libero, tincidunt ut aliquam at, molestie in quam. Aenean rhoncus vehicula hendrerit.

2.3 conclusion

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

Bibliography

Publications