

# **Interface Engineering in CoFeB-based Spintronic Devices for Sensing and Memory Applications**

**AKHIL K RAMESH**



**CENTRE FOR APPLIED RESEARCH IN ELECTRONICS**

**INDIAN INSTITUTE OF TECHNOLOGY DELHI**

**October 2022**

© Indian Institute of Technology Delhi (IITD), New Delhi 2022

# **Interface Engineering in CoFeB-based Spintronic Devices for Sensing and Memory Applications**

by

**AKHIL K. RAMESH**

**Centre for Applied Research in Electronics**

Submitted

*in fulfillment of the requirements of the degree of Doctor of philosophy*

to the



**INDIAN INSTITUTE OF TECHNOLOGY DELHI**

**October 2022**

## CERTIFICATE

This is to certify that the thesis entitled, “**Interface Engineering in CoFeB based Spintronic Devices for Sensing and Memory Applications,**” submitted by **Mr. AKHIL K. RAMESH** to the Indian Institute of Technology Delhi for the award of the degree of “**Doctor of Philosophy**”, is a record of bonafide research work carried out by him under our guidance and supervision.

In my opinion, the thesis has reached the standard of fulfilling the requirement of all the regulations regarding to the degree. For the award of Joint degree the results contained in this thesis have been submitted to National Yang Ming Chiao Tung University as a part of IITD-NYCU Joint Degree Program.



**Dr. Pushparaj Singh**

Centre for Applied Research in Electronic  
Indian Institute of Technology Delhi  
New Delhi-110016, India



**Dr. Yuan-Chieh Tseng**

Department of Material Science and Engineering  
National Yang Ming Chiao Tung University,  
Hsin-Chu, Taiwan 30010, ROC

# *Acknowledgements*

Foremost, I would like to express my sincere gratitude to both of my thesis supervisors *Prof. Pushparaj Singh* and *Prof. Yuan Chieh Tseng* for the continuous support, motivation, valuable guidance, and immense knowledge. Their continuous encouragement, patience and prompt advices have helped me to broaden my views and knowledge in this journey. They have devoted a lot of his time for technical and nontechnical discussions. Also, they have helped me a lot in preparing manuscripts for journals and in thesis writing. Their contribution plays a pivotal role in building a research career.

I am also obliged to *Prof Samaresh Das*, for being constant source of support and encouragement. Also, I would like to extend my sincere gratitude to my doctoral committee members from IIT Delhi *Prof. Ananjan Basu* and *Prof. Pranab Kishor Muduli*, for their efforts in the committee with insightful comments and giving valuable suggestions during the evolution of this research work. I would also like to acknowledge *Prof. Arthur N. Ustinov* for the insightful discussions. Further, I extend my sincere thanks to all the faculty members of the Centre for Applied Research in Electronics (CARE), IIT Delhi. In addition, I would like to thank the coordinators of IITD-NYCU Joint Degree Program for providing me an opportunity to do my research in Taiwan which is the epicentre of semiconductor technology.

I would like to thank Nano Facility Centre (NFC) of NYCU Taiwan, Taiwan Semiconductor Research Institute (TSRI) and Nano Research Facility (NRF) of IIT Delhi for providing the world-class fabrication and characterization facilities. I am thankful to Ministry of Human Resource Development (MHRD), India and Ministry of Science and technology (MOST), Taiwan for funding the research.

I am thankful to *Dr. Ramesh P.*, the one who showed me the way towards this beautiful world of research and my dear friend *Dr. Vaibhav Rana*, who showed the lights in this journey by imparting the microfabrication skills. I appreciate the company of former and current researchers at Microelectronics Lab, IIT Delhi, especially *Dr. Veerendra Dhyani*, *Dr. Bhagaban Behera*, *Dr. Wasi Uddin*, *Dr. Akshay Moudgil*, *Mr. Pragyey Kumar Kaushik*, *Mr. John Wellington*, *Dr. Pratisha Gangwar*, *Mr. Dhairya Singh Arya*, *Mr. Sushil Kumar*, *Mrs. Alka Jakhar*, *Mrs. Akanksha Mishra*, *Mr. Sumit Sharma* and *Mr. Manu Garg*. I would also like to thank all the members of microelectronics CARE, *Mr. Pranav Kumar Shrivastava*, *Mrs. Ruchi Shrivastava*, *Mr. Shakti Singh* and the little *Smahi Shrivastava* for their care, support,

and love. I extend my thanks to friends in NYCU : *KM Chen , Yu Han Huang , Mu Ting , Justine, Jerry ,Yu-Lon* and *Nian-Yu* without whom my research would not have been possible. In particular, I would like to thank *Dr. Chih-Wei* who was my next go to person in case of any doubts. I would also like to mention the efforts of *Dr. Sankalp Kumar Singh* for the support he provided me at NYCU, Taiwan

Finally, I would like to express my deepest feelings of gratitude to all my family members, especially my parents, my brother and my in laws for their unconditional love, support and encouragement. Above all, I am immensely thankful to my wife, Arya, for her patience and support during my journey of Ph. D., which I cannot express in words and would say that I am tremendously lucky to have you by my side.

“Matha Pitha Guru Daivam”– A very popular phrase in Sanskrit meaning Mother, Father , Teacher and God insists us to be grateful to those who create us, teach us, care us and inspire us to live. It also conveys that mother and father – the first and foremost teachers, along with each and every person from whom we learn new things and build the life should be considered as teachers and thanked as they are the real Gods who build our life.



**Akhil K Ramesh**

*Dedicated to my  
Teachers*

## Abstract

Integration of magnetic thin films with existing silicon technology has enabled rapid developments in the field of sensing and memory applications. The electronic spin characteristics of magnetic materials are used in the development of spintronic devices. When the resistance of the material changes due to an external magnetic field, this change in resistance is magnetoresistance. Magnetoresistance has a long history of development (AMR, GMR, TMR, etc.) and a lot of research groups across the world are utilizing various magnetoresistance effects for spintronic device development. Modern magnetic random access memory (MRAM) technology relies on the magnetic tunnel junction (MTJ) consisting of the state-of-the-art CoFeB/MgO/CoFeB sandwich structure responsible for the tunnel magnetoresistance (TMR). This research is focused on the development of sensitive, cost-effective, and industry-friendly spintronic sensors and the optimization of magnetic Tunnel Junctions (MTJ) used for spintronic memories.

In this dissertation, the development of CoFeB based spintronic sensors and further modifications made on the CoFeB layer by the addition of thin layers to develop a memory device have been reported. The importance of the interface between the sensing layer and the successive layer and the performance of the device due to interface engineering has been investigated experimentally and analytically for spintronic memory application. Magnetostrictive ferromagnetic material is selected for the strain sensing application and CoFeB is considered as the best candidate due to its wide usage in magnetic tunnel junctions for sensing and memory applications. Spintronic strain sensor was developed on flexible substrate and the resistance change was observed based on anisotropy magnetoresistance (AMR). The device shows a good sensitivity at low magnetic fields on flexible substrate (GF: ~4.5) for an applied strain up to 30  $\mu\text{m}/\text{m}$ . Further, for deep investigation and understanding the domain change and confirm magnetostriction, micro magnetic simulation has been performed using object oriented micro magnetic framework (OOMMF). The simulation results have confirmed that the coercivity ( $H_c$ ) of the spintronic flexible strain sensor increases with the application of stress, which was earlier observed in the magnetic measurements. Then the heterostructure formed with CoFeB and MgO was optimized for perpendicular magnetic anisotropy (PMA) and during this process it was found that CoFeB/MgO heterostructure can be used for the development of Anomalous Hall effect (AHE) based biosensors. The

heterostructure interface can generate stable interfacial perpendicular anisotropy and features a high magnetic tunneling effect. An enzyme-linked immunosorbent assay (ELISA) based AHE magnetic biosensor was developed through TESUD functionalization. Through several sets of magnetic layer thickness, this work also explored the optimization process of ferromagnetic layer used. The proposed Spintronics-based Anomalous Hall sensors are compatible with semiconductor fabrication technology and can be effectively miniaturized and integrated with semiconductor chips, which has the advantage of reducing manufacturing cost and power consumption. Compared with traditional biological colorimetric measurements, it has more advantages in quantification and immediacy.

In the later part of this dissertation, the interface in CoFeB/MgO heterostructure is further studied to understand the effect of roughness in spintronic memory performance. A new roughness model was developed for the atomistic magnetic simulation of the CoFeB/MgO interface. This roughness model was used for investigating the damping of CoFeB/MgO films and the effective damping constant  $\alpha$  was accurately predicted for ferromagnetic layers of less than 2 nm using this model. This roughness model is further used in the performance study of the MTJ used for Spin Transfer Torque (STT) MRAM application. Later on, the free layer interface of MTJ is modified with thin Mg-layer insertion. The performance of MTJ with and without Mg-insertion is studied experimentally and validated using atomistic simulation. The Mg-modified interface was shown to enhance breakdown-voltage while reducing switching current and asymmetric switching behavior, with a moderate sacrifice in perpendicular magnetic anisotropy, tunneling magneto-resistance, and resistance-area product. This performance trade-off was observed in all MTJs, regardless of cell size (180, 130 and 80nm; each size has been tested with at least 20 cells). A spin-dependent band diagram was constructed to correlate the tunneling/switching properties of the MTJ with such trade-off scenario.

In summary, the dissertation is dealing with the study of CoFeB ferromagnetic layer for inverse magnetostrictive sensor fabrication on flexible substrate, investigation of interface formed in CoFeB/MgO heterostructure used for magnetic sensor applications and modification of the interface for STT-MRAM application.

## सार

मौजूदा सिलिकॉन प्रौद्योगिकी के साथ चुंबकीय पतली फिल्मों के एकीकरण ने संवेदन और स्मृति अनुप्रयोगों के क्षेत्र में तेजी से विकास को सक्षम किया है। स्पिंट्रॉनिक उपकरणों के विकास में चुंबकीय सामग्री की इलेक्ट्रॉनिक स्पिन विशेषताओं का उपयोग किया जाता है। जब बाहरी चुंबकीय क्षेत्र के कारण सामग्री का प्रतिरोध बदलता है, तो प्रतिरोध में यह परिवर्तन चुंबकत्व है। मैग्नेटोरेसिस्टेंस का विकास का एक लंबा इतिहास है (AMR, GMR, TMR, आदि) और दुनिया भर में बहुत सारे शोध समूह स्पिंट्रॉनिक डिवाइस विकास के लिए विभिन्न मैग्नेटोरेसिस्टेंस प्रभावों का उपयोग कर रहे हैं। आधुनिक चुंबकीय रैंडम एक्सेस मेमोरी (MRAM) तकनीक चुंबकीय सुरंग जंक्शन (MTJ) पर निर्भर करती है जिसमें सुरंग मैग्नेटोरेसिस्टेंस (टीएमआर) के लिए जिम्मेदार अत्याधुनिक CoFeB/MgO/CoFeB सैंडविच संरचना शामिल है। यह शोध संवेदनशील, लागत प्रभावी और उद्योग के अनुकूल स्पिंट्रॉनिक सेंसर के विकास और स्पिंट्रॉनिक यादों के लिए उपयोग किए जाने वाले चुंबकीय सुरंग जंक्शन (MTJ) के अनुकूलन पर केंद्रित है।

इस शोध प्रबंध में, CoFeB आधारित स्पिंट्रॉनिक सेंसरों के विकास और एक मेमोरी डिवाइस विकसित करने के लिए पतली परतों को जोड़कर CoFeB परत पर किए गए और संशोधनों की सूचना दी गई है। सेंसिंग लेयर और क्रमिक परत के बीच इंटरफेस के महत्व और इंटरफेस इंजीनियरिंग के कारण डिवाइस के प्रदर्शन को स्पिंट्रॉनिक मेमोरी एप्लिकेशन के लिए प्रयोगात्मक और विश्लेषणात्मक रूप से जांचा गया है। स्ट्रेन सेंसिंग एप्लिकेशन के लिए मैग्नेटोस्ट्रिक्टिव फेरोमैग्नेटिक मैटेरियल का चयन किया जाता है और सेंसिंग और मेमोरी अनुप्रयोगों के लिए चुंबकीय सुरंग जंक्शनों में इसके व्यापक उपयोग के कारण CoFeB को सबसे अच्छा उम्मीदवार माना जाता है। स्पिंट्रॉनिक स्ट्रेन सेंसर को लचीले सबस्ट्रेट पर विकसित किया गया था और अनिसोट्रॉपी मैग्नेटोरेसिस्टेंस (AMR) के आधार पर प्रतिरोध परिवर्तन देखा गया था। डिवाइस लचीला सबस्ट्रेट (जीएफ: ~ 4.5) पर कम चुंबकीय क्षेत्रों में 30  $\mu\text{m/m}$  तक लागू तनाव के लिए एक अच्छी संवेदनशीलता दिखाता है। इसके अलावा, गहन जांच और डोमेन परिवर्तन को समझने और मैग्नेटोस्ट्रिक्शन की पुष्टि करने के लिए, ऑब्जेक्ट ओरिएंटेड माइक्रो मैग्नेटिक फ्रेमवर्क (OOMMF) का उपयोग करके माइक्रो मैग्नेटिक सिमुलेशन किया गया है। सिमुलेशन परिणामों ने पुष्टि की है कि स्पिंट्रॉनिक फ्लेक्सिबल स्ट्रेन सेंसर की ज़बरदस्ती ( $H_c$ ) तनाव के आवेदन के साथ बढ़ जाती है, जिसे पहले चुंबकीय माप में देखा गया था। तब CoFeB और MgO के साथ गठित हेटरोस्ट्रक्चर को लंबवत चुंबकीय अनिसोट्रॉपी (PMA) के लिए अनुकूलित किया गया था और इस प्रक्रिया के दौरान यह पाया गया कि CoFeB/MgO हेटरोस्ट्रक्चर का उपयोग एनोमलस हॉल इफेक्ट (AHE) आधारित बायोसेंसर के विकास

के लिए किया जा सकता है। हेटरोस्ट्रक्चर इंटरफेस स्थिर इंटरफेसियल लंबवत अनिसोट्रॉपी उत्पन्न कर सकता है और एक उच्च चुंबकीय सुरंग प्रभाव पेश करता है। एक एंजाइम से जुड़े इम्युनोसॉरबेंट परख (ELISA) आधारित AHE चुंबकीय बायोसेंसर को TESUD कार्यात्मककरण के माध्यम से विकसित किया गया था। चुंबकीय परत मोटाई के कई सेटों के माध्यम से, इस काम ने इस्तेमाल की जाने वाली फेरोमैग्नेटिक परत की अनुकूलन प्रक्रिया का भी पता लगाया। प्रस्तावित स्पिंट्रोनिक्स-आधारित एनोमलस हॉल सेंसर सेमीकंडक्टर फैब्रिकेशन तकनीक के साथ संगत हैं और इसे सेमीकंडक्टर चिप्स के साथ प्रभावी ढंग से छोटा और एकीकृत किया जा सकता है, जिसमें विनिर्माण लागत और बिजली की खपत को कम करने का लाभ है। पारंपरिक जैविक वर्णमिति माप की तुलना में, परिमाणीकरण और तात्कालिकता में इसके अधिक फायदे हैं।

इस शोध प्रबंध के बाद के भाग में, स्पिंट्रोनिक स्मृति प्रदर्शन में खुरदरापन के प्रभाव को समझने के लिए CoFeB/MgO हेटरोस्ट्रक्चर में इंटरफेस का और अध्ययन किया गया है। CoFeB/MgO इंटरफेस के परमाणु चुंबकीय सिमुलेशन के लिए एक नया खुरदरापन मॉडल विकसित किया गया था। इस खुरदरापन मॉडल का उपयोग CoFeB/MgO फिल्मों की जांच के लिए किया गया था और इस मॉडल का उपयोग करके 2 nm से कम की फेरोमैग्नेटिक परतों के लिए प्रभावी स्थिरांक का सटीक अनुमान लगाया गया था। यह खुरदरापन मॉडल आगे स्पिन ट्रांसफर टॉर्क (STT) MRAM एप्लिकेशन के लिए उपयोग किए जाने वाले MTJ के प्रदर्शन अध्ययन में उपयोग किया जाता है। बाद में, MTJ के फ्री लेयर इंटरफेस को पतली Mg-लेयर इंसर्शन के साथ संशोधित किया गया है। Mg-सम्मिलन के साथ और बिना MTJ के प्रदर्शन का प्रयोगात्मक रूप से अध्ययन किया जाता है और परमाणु सिमुलेशन का उपयोग करके मान्य किया जाता है। Mg-संशोधित इंटरफेस को ब्रेकडाउन-वोल्टेज को बढ़ाने के लिए दिखाया गया था, जबकि स्विचिंग करंट और एसिमेट्रिक स्विचिंग व्यवहार को कम करते हुए, लंबवत चुंबकीय अनिसोट्रॉपी, टनलिंग मैग्नेटो-प्रतिरोध और प्रतिरोध-क्षेत्र उत्पाद में एक मध्यम बलिदान के साथ। सेल आकार (180, 130 और 80nm; प्रत्येक आकार का कम से कम 20 सेल के साथ परीक्षण किया गया है) की परवाह किए बिना, सभी एमटीजे में यह प्रदर्शन देखा गया था। ऐसे ट्रेड-ऑफ़ परिदृश्य के साथ MTJ के टनलिंग/स्विचिंग गुणों को सहसंबंधित करने के लिए एक स्पिन-आश्रित बैंड आरेख का निर्माण किया गया था।

संक्षेप में, शोध प्रबंध लचीले सबस्ट्रेट पर उलटा मैग्नेटोस्ट्रिक्टिव सेंसर निर्माण के लिए CoFeB फेरोमैग्नेटिक परत के अध्ययन से संबंधित है, चुंबकीय सेंसर अनुप्रयोगों के लिए उपयोग किए जाने वाले CoFeB/MgO हेटरोस्ट्रक्चर में गठित इंटरफेस की जांच और STT-MRAM एप्लिकेशन के लिए इंटरफेस का संशोधन।

# Contents

<i>Acknowledgements</i>	i
<i>Abstract</i>	v
<i>₣R</i>	vii
<i>List of Figures</i>	xi
<i>List of Tables</i>	xvii
<i>List of Abbreviation and Symbols</i>	xix
<b>Chapter 1 Introduction</b>	<b>1</b>
1.1 Spintronics Roadmap	4
1.2 Spintronic Device Operation	6
1.2.1 Coherent Tunneling	6
1.2.2 Spin Orbit Effects	7
1.2.3 Applying Electric Field	8
1.2.4 Applying Electromagnetic Waves	8
1.2.5 Spin Seebeck Effect	9
1.2.6 Strain Controlled Devices	10
1.3 Spintronic Memory and Sensors	11
1.4 Engineering the Properties of Materials and Devices	12
1.4.1 Heterostructures	13
1.4.2 Interface Engineering	14
1.5 Motivation and Objectives	15
1.6 Organization of the Thesis	16
<b>Chapter 2 Magnetostrictive CoFeB-based Spintronic Strain Sensors</b>	<b>27</b>
2.1 Introduction	29
2.2 Magnetostrictive Sense layer	31
2.2.1 Ongoing Research based on Strain Sensors for Flat Surfaces	31
2.2.2 Selection of Materials based on the Ongoing Research	32
2.3 Magnetostrictive Sensor Design for Non Flat surfaces	33
2.4 Device Fabrication	36

2.5	Results and Discussion	36
2.5.1	Magnetic Characterization	37
2.5.2	Characterization using Kerr Microscope	37
2.5.3	Magnetic Domain Change with Stress	39
2.5.4	Hysteresis Change with Stress	40
2.5.5	Resistance Change with Stress and Gauge Factor Calculation	41
2.6	Summary	43
<b>Chapter 3</b>	<b>Development of CoFeB/MgO-based Spintronic Bio Sensors</b>	<b>47</b>
3.1	Introduction	49
3.1.1	Conventional Bio Sensors	49
3.1.2	Spintronic Bio Sensors	50
3.2	CoFeB Optimization for PMA	51
3.3	Device Fabrication	52
3.3.1	Hall Bar Fabrication	52
3.3.2	Functionalization	53
3.3.3	Bio Sample Preparation	54
3.4	Hall Bar Characterization	56
3.5	Material Characterization	58
3.5.1	Contact Angle Measurements	59
3.5.2	FTIR Spectroscopy	60
3.5.3	X-ray Photoelectron Spectroscopy	61
3.6	Results and Discussion	63
3.6.1	Image Analysis	63
3.6.2	Electrical and Magnetic Testing	64
3.7	Merits and Demerits of the Sensor	66
3.8	Summary	66
<b>Chapter 4</b>	<b>Atomistic Investigation of CoFeB/MgO Interface</b>	<b>73</b>
4.1	Introduction	75
4.1.1	Roughness at the Heterojunction Interface	76

4.1.2	Roughness Study	77
4.2	Atomistic Simulation Software	77
4.3	Roughness Model	79
4.4	Atomistic Simulation	80
4.4.1	Validating the Roughness Model	80
4.4.2	Damping Test	82
4.4.3	Constrained Monte Carlo (CMC) Simulation	84
4.5	Micromagnetic Simulation	85
4.6	Results and Discussion	85
4.4	Summary	89
<b>Chapter 5</b>	<b>CoFeB/MgO Interface Modification of Magnetic Tunnel Junction with Mg-Insertion</b>	<b>95</b>
5.1	Introduction	97
5.2	Device Fabrication	98
5.3	Device Characterization	99
5.3.1	Magnetic Characterization	100
5.3.2	Electrical Characterization	100
5.4	Breakdown Study of Magnetic Tunnel Junction	101
5.4.1	Breakdown Voltage Estimation	101
5.4.2	X-ray Study of Breakdown	102
5.4.3	Barrier Potential analysis of MTJ under breakdown	105
5.5	Size Dependent Analysis of MTJ Parameters	107
5.5.1	Switching Current	107
5.5.2	Breakdown Voltage	108
5.5.3	Resistance Area Product and TMR	108
5.6	Trade Off Analysis by Atomistic Simulation	109
5.6.1	Atomistic Simulation	109
5.6.2	MH simulation	110
5.6.3	CMC simulation	111
5.7	Summary	112

<b>Chapter 6 Conclusion and Future Outlook</b>	119
6.1 Summary of Research	121
6.2 Contribution of Thesis	122
6.3 Future Outlook	123
<i>List of Publications</i>	125
<i>Curriculum Vitae</i>	127

## List of Figures

<b>Figure No:</b>	<b>Title of Figure</b>	<b>Page No:</b>
Figure 1.1	Spin orientation and assigning bits for each orientation	3
Figure 1.2	Spin Current generation methods for spintronic devices	6
Figure 1.3	Schematic representation of Spin polarized tunneling happening in coherent tunneling based spintronic devices	7
Figure 1.4	Schematic comparison of ordinary Hall Effect, spin Hall effect and Anomalous hall effect	8
Figure 1.5	(a) VCMA MTJ device structure (b) energy barrier dependence on the voltage bias	8
Figure 1.6	Spin generation in the ferromagnet layer due to the electromagnetic wave	9
Figure 1.7	Schematic diagram representing the basic (a) spin Seebeck effect (SSE) and (b) spin Peltier effect (SPE) mechanism in an FM/NM bilayer with the inverse spin Hall effect (ISHE) and spin Hall effect (SHE) of the NM layer, respectively.	10
Figure 1.8	(a) Basic principle of operation for straintronic devices showing magnetization switching due to the strain (b) schematic of straintronic memory device with magnetostrictive layer patterned into elliptical shape over the piezoelectric layer	10
Figure 1.9	Major milestones in the development of spintronic sensors and memory devices	11
Figure 1.10	(a) Spintronic MEMS microphone developed by Toshiba corporation (b) Schematic of the MEMS microphone showing the spintronic and MEMS integration	12
Figure 1.11	Some basic combinations of heterostructures used in MTJ with its effect on TMR sign and magnitude.	13
Figure 1.12	Performance parameters of spintronic devices affected by the HM/FM interface	15

Figure 2.1	Spintronic MEMS sensors developed by (a) Kiel University Germany (b) Bielefeld university Germany and (c) Toshiba corporation	32
Figure 2.2	Micromagnetic model designed for the hall bar structure for assigning the anisotropy values	35
Figure 2.3	Fabrication process flow used in the development of Magnetostrictive Flexible Strain Sensor based on CoFeB sense layer over PET substrate	36
Figure 2.4	The MH measurements for (a) In plane magnetic anisotropy and (b) Out of plane anisotropy	37
Figure 2.5	(a) Sensing principle used to calculate the strain . (b) Molds prepared with its corresponding strain values (c) Attaching the MFSS on the mold for strain dependent testing.	38
Figure 2.6	(a) Kerr microscope measurement setup used for the strain measurement visualization in presence of magnetic field provided by (b) magnets to (c) the flexible sample mounted on the molds in between the magnets	39
Figure 2.7	The change in domains for different strain values at 50 Oe magnetic field applied during the (a) Kerr microscope measurement and (b) micromagnetic simulation	40
Figure 2.8	Change in Hysteresis curve at different values of strain acting on the magnetostrictive sense layer	40
Figure 2.9	Comparison of hysteresis change due to the strain applied on the magnetostrictive strain sensor	41
Figure 2.10	Resistance change observed for the magnetostrictive strain sensor at different strain values showing the variation in resistance at the $H_c$ values.	42
Figure 2.11	Change in resistance with respect to the strain at different magnetic fields. The small deviations can be seen at higher value of strain as shown in the inset	43
Figure 3.1	Schematic showing the conventional color based biomolecule detection using Sandwich double-antibody ELISA	50

Figure 3.2	(a) Schematic diagram of AHE sensor (b) Cross-section of AHE sensor showing functionalization of sandwich ELISA module	51
Figure 3.3	MH curves for samples with CoFeB thickness (a)1.1nm , (b) 1.2nm , (c) 1.3 nm and (c) 1.4nm showing the in plane (IP) and out of plane (OP) measurements	52
Figure 3.4	Schematic illustration showing biosensor fabrication process with fabricated hall bar device in the inset	53
Figure 3.5	Anomalous Hall resistance measured for CoFeB thickness (a) 1.1nm (b) 1.2nm (c) 1.4nm with 15% and 30% concentration of magnetic microbeads; (d) Change in voltage difference at different volumes of the magnetic particle mixture solution during ON/OFF test	58
Figure 3.6	Surface contact angle measurements before and after functionalization and side-view image showing changes in water droplets under the effects of TESUD surface modification	60
Figure 3.7	FTIR results showing the characteristic peaks of TESUD functionalization and antibody binding is highlighted	61
Figure 3.8	(a) XPS results with TESUD functionalized on Ta capping layer of sensor; (b) Peptide bond; (c) C 1s; (d) N 1s; and (e) O 1s orbital domain immobilization of the antibody by the TESUD functional group	62
Figure 3.9	(a) Distribution of magnetic microbeads bound to sandwich ELISA as a function of CA125 concentration, and corresponding fitting curves obtained using the 4PL model	64
Figure 3.10	VSM measurements of CA125 concentrations	65
Figure 3.11	AHE measurement of CA125 concentrations, with variations in saturation magnetization shown in the inset	66
Figure 4.1	Same $R_a$ value for three different surface topologies.	77
Figure 4.2	Schematic showing the VAMPIRE simulation architecture	78
Figure 4.3	The spin orientations of the CoFeB layer showing red color for atoms oriented in one direction and blue for the opposite direction. Transition is through white.	79

Figure 4.4	Schematic illustration showing our model containing the effects of roughness: (a) and (b) Peaks and troughs; (c) $R_{max}$ did not exceed two atomic layers to prevent extreme values from affecting the simulation results, and to prevent effects similar to those of diffusion	80
Figure 4.5	(a) Comparison of roughness (determined by the number of seed points) in CoFeB free layers (FL) of various thicknesses (b) schematic illustration of interface roughness variation with respect to seed points	81
Figure 4.6	Comparison of damping results between the roughness system and the original system, where the thickness of the ferromagnetic layer was 1.3nm.	83
Figure 4.7	(a) Effective damping constant ( $\alpha_{eff}$ ) as a function of $Rq$ and CoFeB thickness; (b) Comparison of damping constant as a function of roughness in previous theoretical [20] and experimental [22] studies	84
Figure 4.8	Resistance versus applied current density (R–J curves): Experimental data and predicted values	86
Figure 4.9	Graphs showing switching times for $AP \rightarrow P$ and $P \rightarrow AP$ switching under various roughness values: (a) $Rq = 0\text{\AA}$ , (b) $Rq = 0.3\text{\AA}$ (c) $Rq = 0.5\text{\AA}$ and (d) $Rq = 0.9\text{\AA}$	87
Figure 4.10	Switching time difference of 1ns observed from minimum to maximum roughness change in (a) $AP$ to $p$ and (b) $P$ to $AP$ switching. (c) The decrease in energy barrier when the roughness is increased.	87
Figure 4.11	Switching from an $AP$ to a $P$ state using CMC simulation in VAMPIRE with domain configurations showing the number of atoms that switched to 90 degrees was positively correlated with the degree of roughness	88
Figure 5.1	Simplified MTJ stacks ((a): w/o-Mg; (b): w-Mg) for in-situ X-ray experiment and electrical characterization.	99

Figure 5.2	Schematic illustration of fabrication process flow in which the Mg layer will be deposited along with the MTJ stacks for w-Mg MTJ.	99
Figure 5.3	(a) M-H loops and (b) SPD diagrams of w/o-Mg (blue) and w-Mg (red) films	100
Figure 5.4	R- $I_{\text{switch}}$ curves (averaging 30 MTJ cells) for w-Mg and w/o-Mg MTJs with values of $I_{\text{switch}}$ for AP $\rightarrow$ P and P $\rightarrow$ AP	101
Figure 5.5	(a) RVS dielectric breakdown test results from w/o-Mg and w-Mg MTJs under positive bias (filled symbols) and negative bias (open symbols) with insets illustrating RVS measurements in terms of bias polarity with respect to charge flow direction; (b) I-V curves (open symbols) and Simon fitting (solid lines) for w/o-Mg and w-Mg MTJs	102
Figure 5.6	In-situ setup of X-ray experiment used to probe MTJ dielectric breakdown (taking w-Mg as an example).	103
Figure 5.7	(a) Fe L2/L3-edge; (b) Co L2/L3-edge; and (c) O K-edge XAS spectra of w/o-Mg MTJs before and after breakdown (BD); (d) Fe L2/L3-edge; (e) Co L2/L3-edge; and (f) O K-edge XAS spectra of w-Mg MTJs before and after BD (colored bars in (c) and (f) highlight changes in pre-edge features)	104
Figure 5.8	Schematic illustration showing band structures (taking 180-nm MTJ as an example) with $\Phi$ values obtained from Fig. 2(b): (a) w/o-Mg MTJ with positive bias (corresponding to AP $\rightarrow$ P switch) and (b) negative bias (corresponding to P $\rightarrow$ AP switch); (c) w-Mg MTJ under positive and (d) negative bias	106
Figure 5.9	$I_{\text{switch}}-V$ curves (averaging 30 MTJ cells) for w-Mg and w/o-Mg MTJs with cell sizes of (a) 180, (b) 130, and (c) 80 nm with values of $I_{\text{switch}}$ for AP $\rightarrow$ P and P $\rightarrow$ AP presented in figure panels for comparison	107
Figure 5.10	VBD (at 63% failure rate) with polarity dependence (+/- bias) for w/o-Mg and w-Mg MTJs with cell sizes of (a) 180, (b) 130, and (c) 80 nm	108

Figure 5.11	Distribution plots of MR% versus RA for w/o-Mg and w-Mg MTJs (approximately 30 cells each) with cell sizes of (a) 180, (b) 130, and (c) 80 nm with insets showing top-view micrograph images of cells	109
Figure 5.12	M-H curve obtained from atomistic simulation of w/o-Mg and w-Mg MTJs	110
Figure 5.13	(a) Switching energy barrier curves of w/o-Mg and w-Mg MTJs; (b) domain configurations obtained from atomistic simulations of w/o-Mg (upper) and w-Mg (lower) MTJs in various stages (45°, 75°, 90°, 105°, and 135°) of free-layer switching from up spin (blue) to downspin (red) (white portions represent atoms involved in in-plane magnetization).	111

## List of Tables

<b>Table No:</b>	<b>Title of Table</b>	<b>Page No:</b>
Table 1.1	The commonly used materials for reference layer , barrier , free llayer and Pinning layer of an MTJ	13
Table 2.1	Gauge factor comparison of sensors using magnetostrictive sense layers	32
Table 2.2	Magnetoelastic anisotropy constant calculated for different strain values.	34
Table 2.3	Simulation parameters used for micromagnetic simulation of MFSS	35
Table 3.1	Reagents used in bio sample preparation	55
Table 3.2	Shows the different standards and the method of preparing lower concentrations from higher concentration.	56
Table 4.1	Atomistic simulation parameters for damping study	83
Table 6.1	Performance comparison of the interface engineered MTJ	123



## *List of Abbreviations and Symbols*

### *Abbreviations*

MTJ	Magnetic Tunnel Junction
MEMS	Micro Electromechanical system
MRAM	Magneto-Resistive Random Access Memory
TMR	Tunneling Magneto-Resistance
GMR	Giant Magneto-Resistance
AMR	Anisotropy Magneto-Resistance
PMA	Perpendicular Magnetic Anisotropy
STT	Spin Transfer Torque
SOT	Spin Orbit Torque
CMOS	Complementary Metal Oxide Semiconductor
TDDB	Time-Dependent Dielectric-Breakdown
FM	Ferro magnet
NM	Non Magnet
HM	Heavy Metal
FTIR	Fourier Transform Infrared Range
TMDCs	Transition Metal Dichalcogenides
FET	Field Effect Transistor
SHE	Spin Hall Effect
AHE	Anomalous Hall Effect
VCMA	Voltage-Controlled Magnetic Anisotropy

SSE	Spin Seebeck effect
SPE	Spin Peltier effect
ISHE	Inverse Spin Hall Effect
RF	Radio Frequency
MR	Magnetoresistance
SAF	Synthetic antiferromagnets
REE	Rashba Edelstein Effect
DMI	Dzyaloshinskii–Moriya interaction
MFSS	Magnetostrictive Flexible Strain Sensor
ELISA	enzyme-linked immunosorbent assay
TESUD	Triethoxysilylundecanal
CMC	Constrained Monte Carlo
GF	Gauge Factor
IBE	Ion Beam Etching

## *Symbols*

$\lambda$	Magnetostriction Coefficient
$\Phi$	Barrier Height
$\sigma$	Stress
$\varepsilon$	Strain
$J$	Current Density
$M_s$	Saturation Magnetization
$\alpha$	Damping constant
$V$	Voltage
$R$	Resistance
$r$	Radius of curvature
$t$	Thickness
$\gamma$	Gyromagnetic ratio
$A_{ex}$	Exchange stiffness
$eV$	Electron Volt
$S$	localized magnetic spin
$K_\sigma$	Magnetoelastic anisotropy constant
$K_u$	Volume anisotropy constant
$H$	Magnetic field
$M$	Magnetization
$R_q$	Root mean square roughness