

TABLE OF CONTENTS

CERTIFICATE.....	i
ACKNOWLEDGEMENTS	ii
ABSTRACT.....	iii
TABLE OF CONTENTS	v
LIST OF FIGURES	x
LIST OF TABLES.....	xv
1. INTRODUCTION.....	1
1.1 Introduction.....	1
1.2 Emerging Smart Applications: Overview of Internet of Things.....	2
1.2.1 Global Market of IoT	3
1.2.2 Prospective Applications of IoT	4
1.2.3 Design Requirement of IoT.....	6
1.3 Self-Powered IoT using Energy Harvesting	7
1.4 Challenges faced by the Energy-Autonomous IoT nodes.....	9
1.4.1 Increasing Static Power Consumption	9
1.4.2 Unsteady Power Supply	11
1.5 Normally-OFF Computing.....	11
1.6 Asynchronous Circuit	13
1.7 Energy-Efficient Computing for IoT Applications.....	13
1.8 Thesis Contribution.....	14
1.9 Thesis Organization	15
References.....	16
2. LITERATURE SURVEY.....	21
2.1 Introduction.....	21
2.2 Embedded Memories in Modern Computing Systems	22
2.2.1 Memory Technology Trend	22
2.2.2 Memory System Requirement for Emerging Applications.....	23
2.2.3 Challenges with the Conventional Memory Technology	25
2.2.4 Existing Solutions for Low Power Memory Design.....	27
2.2.4.1 Alternative Bitcell Design	27
2.2.4.2 Assist Circuit	28
2.2.4.3 Sensing Innovations.....	29

2.2.4.4	Data Retention Mode.....	31
2.3	Embedded Non-Volatile Memory Technology	31
2.4	Logic Circuit in Modern Computing System.....	34
2.4.1	Reversible Logic	35
2.4.2	Near-Threshold Logic	36
2.5	Summary	37
	References.....	38
3.	HYBRID SRAM CELL DESIGN FOR NORMALLY-OFF APPLICATIONS....	46
3.1	Introduction.....	46
3.2	Hybrid Memory	47
3.3	Proposed Hybrid SRAM Cells.....	48
3.3.1	Hybrid 7T SRAM Cell.....	48
3.3.1.1	Structure of proposed hybrid 7T SRAM cell.....	49
3.3.1.2	Operational modes of proposed hybrid 7T SRAM Cell.....	49
3.3.1.2.1	Write/Backup operation	49
3.3.1.2.2	Read operation.....	52
3.3.1.2.3	Restore operation.....	52
3.3.1.3	Circuit-level analysis	52
3.3.2	Hybrid 8T SRAM Cell.....	56
3.3.2.1	Structure of hybrid 8T SRAM cell	56
3.3.2.2	Operational modes of hybrid 8T SRAM cell.....	56
3.3.2.2.1	Write operation.....	56
3.3.2.2.2	Read operation.....	57
3.3.2.2.3	Backup operation.....	57
3.3.2.2.4	Restore operation.....	58
3.3.2.3	Circuit-level analysis	59
3.3.3	Hybrid 11T SRAM Cell.....	61
3.3.3.1	Structure of hybrid 11T SRAM cell	61
3.3.3.2	Operational modes of hybrid 11T SRAM cell.....	62
3.3.3.2.1	Write operation.....	62
3.3.3.2.2	Read operation.....	62
3.3.3.2.3	Backup operation.....	63
3.3.3.2.4	Restore operation.....	63
3.3.3.3	Circuit-level analysis	63

3.4	Simulation Result and Comparative Analysis	65
3.4.1	Energy estimation	66
3.4.2	Area estimation	67
3.5	Conclusion	68
	References	69
4.	HYBRID MULTI-STORAGE SRAM CELL WITH WRITE ASSIST CIRCUIT..	72
4.1	Introduction.....	72
4.2	Hybrid Multi-Storage SRAM Cell.....	73
4.2.1	Structure of hybrid multi-storage SRAM cell.....	73
4.2.2	Operational modes of multi-storage SRAM cell.....	74
4.2.2.1	Normal operation	74
4.2.2.2	Store operation.....	75
4.2.2.3	Load operation.....	75
4.2.2.4	Switch operation.....	76
4.2.3	Circuit-level analysis.....	77
4.3	Write Assist Circuit for Hybrid SRAM Cell.....	78
4.3.1	Proposed write assist/termination circuit for single-bit hybrid SRAM cell.....	79
4.3.1.1	Operational modes of self-terminating SRAM cell	80
4.3.1.1.1	Write operation.....	80
4.3.1.1.2	Restore operation.....	81
4.3.1.1.3	Normal memory operation	82
4.3.2	Proposed write assist/termination circuit for multi-storage hybrid SRAM cell..	82
4.3.2.1	Operational modes of self-terminating multi-storage SRAM cell.....	82
4.3.2.1.1	Store operation	83
4.3.2.2	Simulation Results	86
4.3.2.2.1	Comparative analysis of proposed multi-storage SRAM cell with existing multi-storage SRAM cell	87
4.4	Conclusion	88
	References	89
5.	STATE RETENTIVE HYBRID D FLIP-FLOP	91
5.1	Introduction.....	91
5.2	Existing Stata Retention Flip-Flop (SRFF).....	92
5.2.1	Mutoh MT-CMOS Flip-Flop	93
5.2.1.1	Structure of mutoh MT-CMOS flip-flop.....	93

5.2.1.2	Operation of mutoh MT-CMOS flip-flop.....	93
5.2.2	Balloon Flip-flop.....	94
5.2.2.1	Structure of balloon flip-flop.....	94
5.2.2.2	Operation of balloon flip-flop.....	95
5.2.3	Memory Flip-flop.....	96
5.2.3.1	Structure of memory flip-flop.....	96
5.3	Proposed State Retentive Hybrid D Flip-Flop.....	97
5.3.1	Proposed State Retentive Hybrid Flip-Flop Circuit-I (HFF-I).....	97
5.3.1.1	Structure of hybrid flip-flop (HFF-I).....	97
5.3.1.2	Operational modes of HFF-I.....	98
5.3.1.2.1	Normal operation.....	98
5.3.1.2.2	Backup operation.....	99
5.3.1.2.3	Restore operation.....	100
5.3.2	Proposed State Retentive Hybrid Flip-Flop Circuit-II (HFF-II).....	101
5.3.2.1	Structure of hybrid FF Circuit-II (HFF-II).....	101
5.3.2.2	Operational modes of HFF-II.....	101
5.3.2.2.1	Normal operation.....	102
5.3.2.2.2	Backup operation.....	102
5.3.2.2.3	Restore operation.....	103
5.4	Simulation Result.....	103
5.4.1	Data recovery in various flip-flops.....	104
5.4.2	Power consumption by various flip-flops.....	105
5.4.3	Delay of various flip-flops.....	108
5.4.4	Comparison with state-of-the-art hybrid flip-flop.....	108
5.5	Conclusion.....	112
	References.....	112
6.	HYBRID ASYNCHRONOUS CIRCUIT DESIGN.....	115
6.1	Introduction.....	115
6.2	State-of-the-Art Asynchronous Circuit.....	117
6.3	Proposed Hybrid Asynchronous Circuit.....	118
6.3.1	Proposed Hybrid C-Element.....	119
6.3.1.1	Normal mode.....	119
6.3.1.2	Backup mode.....	119
6.3.1.3	Restore mode.....	120

6.3.2	Proposed Hybrid Half-Buffer.....	121
6.4	Simulation Results and Discussion.....	122
6.5	Conclusion	125
	References.....	126
7.	ENERGY-EFFICIENT LOGIC AND ARITHMETIC CIRCUITS.....	128
7.1	Introduction.....	128
7.2	STT-MTJ based Computational Magnetic Random-Access Memory	130
7.2.1	Implementing logic operations.....	131
7.2.1.1	NAND logic gate	132
7.2.1.2	NOR logic gate	133
7.2.2	Circuit-level analysis.....	133
7.3	SHE-MTJ based Computational Magnetic Random-Access Memory	135
7.3.1	Implementing logic operation	137
7.3.1.1	NAND/AND logic gate	139
7.3.1.2	NOR/OR logic gate	140
7.3.2	Circuit-level analysis.....	141
7.4	Proposed Low-Power Arithmetic Function	142
7.4.1	Circuit-level analysis.....	146
7.5	Conclusion	148
	References.....	149
8.	CONCLUSION AND FUTURE SCOPE.....	152
8.1	Conclusion	152
8.2	Future Scope of Work.....	154
	APPENDIX A.....	155
	APPENDIX B.....	156
	APPENDIX C.....	157
	LIST OF PUBLICATIONS	159
	BRIEF BIOGRAPHY OF CANDIDATE.....	161
	BRIEF BIOGRAPHY OF SUPERVISOR	162