Contents

ACKNOWLEDGEMENTS xi

PREFACE. xiii

PART 1. INFORMATION STORAGE AND THE STATE OF THE ART OF ELECTRONIC MEMORIES. 1

CHAPTER 1. GENERAL ISSUES RELATED TO DATA STORAGE AND ANALYSIS CLASSIFICATION OF MEMORIES AND RELATED PERSPECTIVES 3

- 1.1. Issues arising from the flow of digital information 3
- 1.2. Current electronic memories and their classification 5
- 1.3. Memories of the future. 8

CHAPTER 2. STATE OF THE ART OF DRAM, SRAM, FLASH, HDD AND MRAM ELECTRONIC MEMORIES. 13

- 2.1. DRAM volatile memories. 13
  - 2.1.1. The operating principle of a MOSFET (metal oxide semiconductor field effect transistor). 14
  - 2.1.2. Operating characteristics of DRAM memories 17
- 2.2. SRAM memories 19
- 2.3. Non-volatile memories related to CMOS technology 22

2.3.1. Operational characteristics of a floating gate MOSFET 22
2.3.2. Flash memories. 38
2.4. Non-volatile magnetic memories (hard disk drives – HDDs and MRAMs) 45
2.4.1. The discovery of giant magneto resistance at the origin of the spread of hard disk drives 46
2.4.2. Spin valves 49
2.4.3. Magnetic tunnel junctions 51
2.4.4. Operational characteristics of a hard disk drive (HDD) 51
2.4.5. Characteristics of a magnetic random access memory (MRAM) 54
2.5. Conclusion 56

CHAPTER 3. EVOLUTION OF SSD TOWARD FERAM, FEFET, CTM AND STT-RAM MEMORIES 59

3.1. Evolution of DRAMs toward ferroelectric FeRAMs 60
3.1.1. Characteristics of a ferroelectric material 60
3.1.2. Principle of an FeRAM memory 63
3.1.3. Characteristics of an FeFET memory. 67
3.2. The evolution of Flash memories towards charge trap memories (CTM) 77
3.3. The evolution of magnetic memories (MRAM) toward spin torque transfer memories (STT-RAM) 82
3.3.1. Nanomagnetism and experimental implications 83
3.3.2. Characteristics of spin torque transfer 84
3.3.3. Recent evolution with use of perpendicular magnetic anisotropic materials 88
3.4. Conclusions 90

PART 2. THE EMERGENCE OF NEW CONCEPTS: THE INORGANIC NEMS, PCRAM, RERAM AND ORGANIC MEMORIES 93

CHAPTER 4. VOLATILE AND NON-VOLATILE MEMORIES BASED ON NEMS 95

4.1. Nanoelectromechanical switches with two electrodes 96

4.1.1. NEMS with cantilevers 97
4.1.2. NEMS with suspended bridge 102
4.1.3. Crossed carbon nanotube networks 103
4.2. NEMS switches with three electrodes 106
4.2.1. Cantilever switch elaborated by lithographic techniques 107
4.2.2. Nanoswitches with carbon nanotubes 110
4.2.3. NEMS-FET hybrid memories with a mobile floating gate or mobile cantilever 116
4.4. Conclusion 121

CHAPTER 5. NON-VOLATILE PHASE-CHANGE ELECTRONIC MEMORIES (PCRAM) 123

5.1. Operation of an electronic phase-change memory 125
5.1.1. Composition and functioning of a GST PCRAM 125
5.1.2. The antinomy between the high resistance of the amorphous state and rapid heating 129
5.2. Comparison of physicochemical characteristics of a few phase-change materials 134
5.3. Key factors for optimized performances of PCM memories 137
5.3.1. Influence of cell geometry on the current I_m needed for crystal melting 138
5.3.2. Optimization of phase-change alloy composition to improve performance 143
5.3.3. Influence of nanostructuration of the phase-change material 148
5.3.4. Recent techniques for improvement of amorphization and crystallization rates of phase-change materials 156
5.3.5. Problems related to interconnection of PCRAM cells in a 3D crossbar-type architecture 160
5.4. Conclusion 162

CHAPTER 6. RESISTIVE MEMORY SYSTEMS (RRAM) 165

6.1. Main characteristics of resistive memories 168
6.1.1. Unipolar system 169

6.1.2. Bipolar system 170
6.2. Electrochemical metallization memories 171
6.2.1. Atomic switches 174
6.2.2. Metallization memories with an insulator or a semiconductor. 177
6.2.3. Conclusions on metallization memories 182
6.3. Resistive valence change memories (VCM) 183
6.3.1. The first work on resistive memories. 183
6.3.2. Resistive valence change memories after the 2000s 185
6.3.3. A perovskite resistive memory ($SrZrO_3$) with better performance than Flash memories 186
6.3.4. Electroforming and resistive switching. 189
6.3.5. Hafnium oxide for universal resistive memories? 195
6.4. Conclusion. 198

CHAPTER 7. ORGANIC AND NON-VOLATILE ELECTRONIC MEMORIES. 201

7.1. Flash-type organic memories 204
7.1.1. Flexible FG-OFET device with metal floating gate. 205
7.1.2. Flexible organic FG-OFET entirely elaborated by spin coating and inkjet printing 212
7.1.3. Flexible OFETs with charge-trap gate dielectrics 216
7.1.4. OFETs with conductive nanoparticles encapsulated in the gate dielectric 221
7.1.5. Redox dielectric OFETs 226
7.2. Resistive organic memories with two contacts. 230
7.2.1. Organic memories based on electrochemical metallization 232
7.2.2. Resistive charge-trap organic memories 238
7.3. Molecular memories 244
7.4. Conclusion. 248

CONCLUSION 251

BIBLIOGRAPHY 255

INDEX. 285