

Umberto Celano

Metrology and Physical Mechanisms in New Generation Ionic Devices

Doctoral Thesis accepted by
the KU Leuven and IMEC, Belgium

Contents

1 Introduction	1
1.1 Nonvolatile Memory for Sub-15 nm Node	2
1.2 New Applications, New Needs and Old Problems	4
1.3 Resistive Switching: Bits Made of Filaments.	5
1.4 Objectives and Outline of the Dissertation	6
References	8
2 Filamentary-Based Resistive Switching	11
2.1 Basic Operating Principles	11
2.2 Conductive Bridge Resistive Memory	14
2.2.1 The Electrochemistry in CBRAM	15
2.2.2 The Rate-Limiting Process	17
2.2.3 CBRAM Device Operation.	18
2.2.4 Device Optimization	21
2.3 Oxide-Based Valence Change Memory	24
2.3.1 VCM Device Operation	25
2.3.2 Switching Mechanism and Electron Transport in VCM	27
2.3.3 The Filament as a Quantum Point Contact	28
2.3.4 VCM Device Optimization.	30
2.4 Review of Conductive Filaments Observation	31
2.4.1 Filament Observation in CBRAM	32
2.4.2 Filament Observation in VCM	36
2.5 Summary of the Chapter	39
References	39
3 Nanoscaled Electrical Characterization	47
3.1 Overview	47
3.2 Conductive Atomic Force Microscopy	50
3.2.1 Conductive Tips	52
3.2.2 Contact Forces	54
3.2.3 Artifacts in C-AFM.	56
3.2.4 Electrical Lateral Resolution	60

3.2.5	Effective Emission Area Evaluation	61
3.2.6	Extending C-AFM Current Range	66
3.3	Peak Force: Intermittent Contact Mode	67
3.3.1	Peak Force TUNA Case Studies	70
3.3.2	Electrical Tip-Contact: Dragged Versus Intermittent	73
3.4	Three-Dimensional SPM Tomography	75
3.4.1	Overview of 3D Tomography	76
3.4.2	SPM Tomography	78
3.5	Summary of the Chapter	82
	References	83
4	Conductive Filaments: Formation, Observation and Manipulation	87
4.1	Tip-Induced Filament Formation and Observation	87
4.1.1	Areal Switching	88
4.1.2	Ultra-Scaled Device Sizes with C-AFM	89
4.1.3	The Role of the Tip	91
4.1.4	Resistive Switching C-AFM Versus Devices	93
4.1.5	Filament Observation	96
4.2	C-AFM Probing the Reset State	100
4.2.1	Gap Formation in Cu Filaments	100
4.2.2	Low-Defects Assisted Quantum-Point-Contact	103
4.3	Device De-Process: Filament Observation	107
4.4	Summary of the Chapter	111
	References	111
5	Three-Dimensional Filament Observation	115
5.1	Scalpel SPM for Filament Observation	115
5.2	Tomographic Observation of Cu-Based Filaments	116
5.2.1	CBRAM: Low-Resistive-State Observation	117
5.2.2	CBRAM: High-Resistive-State Observation	119
5.2.3	Cu-Filament Growth Model in Low-Mobility Media	120
5.2.4	Filament Volume Modulation and Multibit Capability	122
5.3	On the Dual Nature of Cu Filament Dissolution	124
5.3.1	A Model for Broken and Nonbroken HRS Filaments	127
5.3.2	A Ruptured Filament Is Not a Conventional Tunnel Junction	129
5.3.3	Hourglass Shaped Cu Filament	130
5.4	Tomographic Filament Observation in VCM	132
5.4.1	Filament Size Modulation in VCM	136
5.5	Summary of the Chapter	139
	References	140
6	Reliability Threats in CBRAM	143
6.1	Reliability Threats of Cu Filaments	143
6.2	Filament Multiplicity as Source of State Instability	144

6.3	Stuck in LRS: A Cu Filament Degeneracy	147
6.4	Summary of the Chapter	149
	References	150
7	Conclusions and Outlook	151
7.1	Filaments Formation and Dissolution	151
7.1.1	Challenges with Tip-Induced Analysis	153
7.2	Filaments 3D Observation	154
7.2.1	Challenges in the Three-Dimensional Observation	156
7.3	Outlook	157
7.3.1	Improving Scalpel SPM	159
	Appendix A: Cellulose Nanopaper Memory	161
	Curriculum Vitae	169