

# Contents

<b>1</b>	<b>Research Background and Motivation</b>	<b>1</b>
1.1	General Concept of Anodic Porous Alumina	1
1.2	Various Applications of Anodic Porous Alumina	2
1.2.1	Applications in Photonic Crystals	2
1.2.2	Applications in Energy Storage and Conversion	3
1.2.3	Applications in Bio-devices	4
1.2.4	Applications in Electronic/Magnetic Devices	5
1.3	Formation Mechanisms of Anodic Porous Alumina	6
1.4	Fabrication Methods for Self-ordered Anodic Porous Alumina	10
1.4.1	Mild Anodization and Hard Anodization	10
1.4.2	Anodization with Prepatterns on Aluminum Substrate	11
1.4.3	Anodic Porous Alumina Formed on Aluminum Grains with Different Crystallographic Orientations	12
1.4.4	Other Anodization Methods	13
1.5	Objectives and Flow of the Present Research	13
	References	15
 <b>Part I Modelling, Numerical Simulation, and Experimental Verification of Self-ordering in Anodic Porous Alumina</b>		
<b>2</b>	<b>Establishment of a Kinetics Model</b>	<b>23</b>
2.1	Introduction	23
2.2	Electric Potential Distribution Within Anodic Porous Alumina	23

2.3	Ion Migration . . . . .	27
2.3.1	Aluminum Ion Migration . . . . .	27
2.3.2	Oxygen Ion Migration . . . . .	30
2.3.3	Relationship Between Aluminum Ion Current Density and Oxygen Ion Current Density Within the Oxide Body . . . . .	32
2.4	Interface Movement Equations . . . . .	33
2.5	Summary . . . . .	34
	References. . . . .	34
<b>3</b>	<b>Numerical Simulation Based on the Established Kinetics Model . . . . .</b>	<b>37</b>
3.1	Introduction . . . . .	37
3.2	Numerical Realization of the Kinetics Model . . . . .	37
3.2.1	Simulation Procedures . . . . .	37
3.2.2	Simulation Parameters . . . . .	39
3.3	Simulation Results and Discussion . . . . .	42
3.3.1	Electric Field-Driven Pore Growth in Anodic Porous Alumina . . . . .	43
3.3.2	Electric Field-Driven Self-ordering in Anodic Porous Alumina . . . . .	48
3.4	Summary . . . . .	58
	References. . . . .	59
<b>4</b>	<b>Experimental Verification I: Growth Sustainability of Nanopore Channels Guided with Pre-patterns . . . . .</b>	<b>61</b>
4.1	Introduction . . . . .	61
4.2	Experimental Methods. . . . .	62
4.2.1	Pretreatment of Aluminum Foils . . . . .	62
4.2.2	Anodization Experimental Setup . . . . .	62
4.2.3	Pre-patterning of Aluminum Surface by Focused Ion Beam Milling . . . . .	63
4.2.4	Microscopic Characterization . . . . .	63
4.3	Results and Discussion . . . . .	63
4.4	Summary . . . . .	72
	References. . . . .	72
<b>5</b>	<b>Experimental Verification II: Substrate Grain Orientation-Dependent Self-ordering . . . . .</b>	<b>75</b>
5.1	Introduction . . . . .	75
5.2	Experiments of Substrate Grain Orientation-Dependent Self-ordering . . . . .	76
5.3	Simulation of Substrate Grain Orientation-Dependent Self-ordering . . . . .	78

5.4	Discussion . . . . .	82
5.4.1	Physical Meaning and Effects of $\beta$ . . . . .	82
5.4.2	Experimental Verification . . . . .	84
5.5	Summary . . . . .	86
	References. . . . .	86

## **Part II Fabrication of Highly Self-ordered Anodic Porous Alumina**

<b>6</b>	<b>Quantitative Evaluation of Self-ordering in Anodic Porous Alumina . . . . .</b>	<b>91</b>
6.1	Introduction . . . . .	91
6.2	Quantitative Evaluation Methods for Porous Patterns in Anodic Porous Alumina. . . . .	92
6.2.1	Radial Distribution Function (RDF). . . . .	92
6.2.2	Angle Distribution Function (ADF). . . . .	92
6.2.3	Angular Orientation Distribution (AOD) . . . . .	93
6.3	Experimental Method . . . . .	95
6.4	Effects of the Quantitative Evaluation Methods. . . . .	97
6.5	Summary . . . . .	104
	References. . . . .	104
<b>7</b>	<b>Fast Fabrication of Self-ordered Anodic Porous Alumina on Oriented Aluminum Grains . . . . .</b>	<b>105</b>
7.1	Introduction . . . . .	105
7.2	Experimental Methods. . . . .	106
7.2.1	Anodization of Aluminum . . . . .	106
7.2.2	Microscopic Characterization . . . . .	106
7.2.3	Quantitative Evaluation of Self-ordering in Porous Patterns. . . . .	108
7.2.4	Statistical Evaluation of Interpore Distance. . . . .	108
7.3	Results and Discussion . . . . .	109
7.3.1	Substrate Grain Orientation-Dependent Self-ordering of Porous Patterns . . . . .	109
7.3.2	Acid Concentration-Dependent Self-ordering of Porous Patterns . . . . .	109
7.3.3	Temperature-Dependent Self-ordering of Porous Patterns. . . . .	111
7.3.4	Voltage-Dependent Self-ordering of Porous Patterns Under HHA and MA Conditions . . . . .	115
7.3.5	Time-Dependent Self-ordering of Porous Patterns . . . . .	121
7.4	Summary . . . . .	124
	References. . . . .	125

### **Part III Electro-Chemo-Mechanical Actuators of Anodic Porous Alumina**

<b>8</b>	<b>Charge-Induced Reversible Bending in Anodic Porous Alumina–Aluminum Composites</b>	129
8.1	Introduction	129
8.2	Direct Observation of the Reversible Bending by Optical Microscope	130
8.3	Detection of the Reversible Bending by In Situ Nanoindentation	133
8.4	Discussion of the Reversible Bending	137
8.5	Summary	140
	References	140
<b>9</b>	<b>Chemomechanical Softening During In Situ Nanoindentation of Anodic Porous Alumina with Anodization Processing</b>	143
9.1	Introduction	143
9.2	Experimental Method	144
9.2.1	Electrochemical Cell Setup	144
9.2.2	In Situ and Ex Situ Nanoindentation	145
9.2.3	Drift Correction Method for Nanoindentation	145
9.2.4	In Situ and Ex Situ Microindentation	147
9.2.5	Electron Microscopic Characterization	148
9.3	Softening During In Situ Nanoindentation	148
9.4	Possible Explanations of the In Situ Softening	153
9.4.1	Electric-Field Assisted Softening of the Oxide	153
9.4.2	Enhancement of Electrochemical Reactions at the Metal/Oxide Interface	154
9.4.3	Enhancement of Dislocation Activities in Aluminum Substrate	154
9.5	TEM Examination of Deformation of Oxide and Aluminum Substrate	155
9.6	Enhancement of Electrochemical Reactions at the Metal/Oxide Interface by High Electric-Field and Stresses	157
9.7	Summary	159
	References	160

<b>10</b>	<b>Conclusions and Future Work. . . . .</b>	<b>161</b>
10.1	Conclusions . . . . .	161
10.2	Future Work . . . . .	164
10.2.1	Modeling and Numerical Simulation . . . . .	164
10.2.2	Fabrication. . . . .	165
10.2.3	Actuation. . . . .	165
	References. . . . .	166
<b>Appendix I: Calculation Program for Pore Channel Growth in Anodic Porous Alumina . . . . .</b>		<b>167</b>
<b>Appendix II: Calculation Program for Evaluation of Self-ordering in Anodic Porous Alumina . . . . .</b>		<b>229</b>

Electro-Chemo-Mechanics of Anodic Porous Alumina  
Nano-Honeycombs: Self-Ordered Growth and Actuation

Cheng, C.

2015, XVII, 278 p. 70 illus., 49 illus. in color., Hardcover

ISBN: 978-3-662-47267-5