

# Contents

## List of Abbreviations *ix*

<b>1</b>	<b>Introduction</b>	<i>1</i>
	References	<i>4</i>
<b>2</b>	<b>Fundamentals</b>	<i>7</i>
2.1	Important Performance Metrics of Etching Processes	<i>7</i>
2.1.1	Etching Rate (ER)	<i>8</i>
2.1.2	Etching Rate Nonuniformity (ERNU)	<i>8</i>
2.1.3	Selectivity	<i>9</i>
2.1.4	Profile	<i>9</i>
2.1.5	Critical Dimension (CD)	<i>9</i>
2.1.6	Line Width and Edge Roughness (LWR and LER)	<i>10</i>
2.1.7	Edge Placement Error (EPE)	<i>10</i>
2.1.8	Aspect Ratio-Dependent Etching (ARDE)	<i>10</i>
2.2	Physisorption and Chemisorption	<i>11</i>
2.3	Desorption	<i>13</i>
2.4	Surface Reactions	<i>14</i>
2.5	Sputtering	<i>15</i>
2.6	Implantation	<i>21</i>
2.7	Diffusion	<i>22</i>
2.8	Transport Phenomena in 3D Features	<i>26</i>
2.8.1	Neutral Transport	<i>27</i>
2.8.2	Ion Transport	<i>30</i>
2.8.3	Transport of Reaction Products	<i>34</i>
2.9	Classification of Etching Technologies	<i>35</i>
	References	<i>39</i>
<b>3</b>	<b>Thermal Etching</b>	<i>43</i>
3.1	Mechanism and Performance Metrics of Thermal Etching	<i>43</i>
3.1.1	Etching Rate and ERNU	<i>43</i>
3.1.2	Selectivity	<i>44</i>
3.1.3	Profile and CD Control	<i>44</i>

3.1.4	ARDE	45
3.2	Applications Examples	45
	References	50
<b>4</b>	<b>Thermal Isotropic ALE</b>	<b>51</b>
4.1	Mechanism of Thermal Isotropic ALE	51
4.1.1	Chelation/Condensation ALE	54
4.1.2	Ligand Exchange ALE	55
4.1.3	Conversion ALE	58
4.1.4	Oxidation/Fluorination ALE	60
4.2	Performance Metrics	62
4.2.1	Etching Rate (EPC)	62
4.2.2	ERNU (EPC Nonuniformity)	67
4.2.3	Selectivity	69
4.2.4	Profile and ARDE	70
4.2.5	CD Control	73
4.2.6	Surface Smoothness	74
4.3	Plasma-Assisted Thermal Isotropic ALE	74
4.4	Applications Examples	75
4.4.1	Area-Selective Deposition	75
4.4.2	Formation of Lateral Devices	77
	References	79
<b>5</b>	<b>Radical Etching</b>	<b>85</b>
5.1	Mechanism of Radical Etching	85
5.2	Performance Metrics	86
5.2.1	Etching Rate and ERNU	86
5.2.2	Selectivity	87
5.2.3	Profile and ARDE	87
5.2.4	CD Control	88
5.3	Applications Examples	88
	References	89
<b>6</b>	<b>Directional ALE</b>	<b>91</b>
6.1	Mechanism of Directional ALE	91
6.1.1	ALE with Directional Modification Step	91
6.1.2	ALE with Directional Removal Step and Modification by Chemisorption and Diffusion	93
6.1.3	ALE with Directional Removal Step and Modification by Reactive Layer Deposition	106
6.2	Performance Metrics	110
6.2.1	Etching Rate (EPC)	110
6.2.2	ERNU (EPC Nonuniformity)	111
6.2.3	Selectivity	112
6.2.4	Profile and ARDE	116

6.2.5	Surface Smoothness and LWR/LER	120
6.3	Applications Examples	123
6.3.1	ALE with Directional Modification Step	123
6.3.2	ALE with Directional Removal Step and Modification by Chemisorption and Diffusion	125
6.3.3	ALE with Directional Removal Step and Modification by Reactive Layer Deposition	127
	References	129
<b>7</b>	<b>Reactive Ion Etching</b>	<b>133</b>
7.1	Reactive Ion Etching Mechanisms	133
7.1.1	Simultaneous Species Fluxes	133
7.1.2	Chemical Sputtering	138
7.1.3	Mixed Layer Formation	141
7.1.4	Role of Etching Products	143
7.2	Performance Metrics	144
7.2.1	Etching Rate	144
7.2.2	ERNU	150
7.2.3	ARDE	150
7.2.4	Selectivity	154
7.2.5	Profile Control	156
7.2.5.1	Sidewall Passivation	157
7.2.5.2	Selection of Etching Species	161
7.2.5.3	Temperature	162
7.2.6	CD Control	165
7.2.7	Surface Smoothness	168
7.2.8	LWR/LER	169
7.3	Applications Examples	173
7.3.1	Patterning	174
7.3.1.1	Self-aligned Patterning	174
7.3.1.2	Extreme Ultraviolet (EUV) Lithography	180
7.3.2	Logic Devices	182
7.3.2.1	Fin Etch	182
7.3.2.2	Gate Etch	184
7.3.2.3	Spacer Etch	187
7.3.2.4	Contact Etch	187
7.3.2.5	BEOL Etch	189
7.3.3	DRAM and 3D NAND Memory	191
7.3.3.1	DRAM Capacitor Cell Etch	191
7.3.3.2	High Aspect Ratio 3D NAND Etch	208
7.3.4	Emerging Memories	210
7.3.4.1	Phase Change Memory (PCM)	211
7.3.4.2	ReRAM	216
	References	217

<b>8</b>	<b>Ion Beam Etching</b>	<b>225</b>
8.1	Mechanism and Performance Metrics of Ion Beam Etching	225
8.2	Applications Examples	226
	References	228
<b>9</b>	<b>Etching Species Generation</b>	<b>231</b>
9.1	Introduction of Low-Temperature Plasmas	231
9.2	Capacitively Coupled Plasmas	237
9.3	Inductively Coupled Plasmas	252
9.4	Ion Energy Distribution Modulation	256
9.5	Plasma Pulsing	259
9.6	Grid Sources	263
	References	266
<b>10</b>	<b>Emerging Etching Technologies</b>	<b>271</b>
10.1	Electron-Assisted Chemical Etching	271
10.2	Photon-Assisted Chemical Etching	273
	References	275
	<b>Index</b>	<b>277</b>