

# Contents

## List of Abbreviations

xiii

<b>1. Introduction</b> .....	<b>1</b>
1.1 Research Scope and Objectives .....	1
1.2 Methodology.....	2
1.2.1 Thermal Stress Issues in Anodic Bonding Process .....	2
1.2.2 Thermal Stress Issues in MEMS Bonding Process .....	3
1.2.3 Materials Characterization, Bonding and MEMS Performance Test .....	3
1.3 Structure of This Thesis .....	4
<b>2. Literature Review</b> .....	<b>7</b>
2.1 Review of MEMS Packaging Technique .....	7
2.1.1 MEMS Packaging Requirements.....	8
2.1.1.1 Impact of Environment.....	9
2.1.1.2 Packaging Structure and Packaging Materials.....	9
2.1.1.3 Interface .....	10
2.1.1.4 Assembly, Packaging and Testing .....	10
2.1.2 MEMS Packaging Level.....	11
2.1.2.1 First Level Packages .....	11
2.1.2.2 Wafer Level Chip Scale Packaging (WL-CSP).....	14
2.1.2.3 System-in-Packaging (SiP) .....	16
2.2 Review of Wafer Bonding Techniques for MEMS.....	18
2.2.1 Wafer Bonding without Intermediate Layers .....	22
2.2.1.1 Anodic Bonding Technique .....	22
2.2.1.2 Fusion Bonding Technique .....	23
2.2.1.3 Surface Activated Bonding Technique .....	24
2.2.2 Wafer Bonding with Metallic Intermediate Layers .....	24
2.2.2.1 Eutectic Bonding Technique .....	24
2.2.2.2 Transient Liquid Phase (TLP) Bonding.....	25
2.2.2.3 Thermocompression Bonding .....	26
2.2.3 Wafer Bonding with Insulating Intermediate Layers .....	27
2.2.3.1 Glass Frit Bonding Technique .....	27
2.2.3.2 Adhesive Bonding Technique .....	27
2.3 Review of Anodic Bonding Materials for MEMS Packaging.....	28
2.3.1 Mempax®, Borofloat® 33 and Pyrex® 7740 .....	28
2.3.2 Low Temperature Co-Fired Ceramic (LTCC) Material.....	29
2.3.3 SD-2 and SW-YY® Glass.....	30
2.3.4 Thin-Glass-Layer .....	31
2.4 Summary and Conclusion.....	32
2.4.1 Problems: Influence of Temperature, Materials on Anodic Bonding for Sensitive MEMS.....	33

2.4.2 State-of-Art.....	33
2.4.3 Solution.....	33
2.4.4 Application.....	34
<b>3. Low Stress Anodic Bonding Theory .....</b>	<b>35</b>
3.1 Thermal Stress Issue in Anodic Bonding Process.....	35
3.2 CLT based Thermal Anodic Bonding Model .....	36
3.2.1 Stress-Strain Relations for the Silicon-Glass Model.....	37
3.2.2 Case Study Silicon and Mempax® Bonding Model .....	46
3.3 Experiment Preparation and Measurements.....	58
3.3.1 Cleaning Procedure.....	59
3.3.2 Preparation for Bonding.....	60
3.3.3 Bonding Results-Optical Inspection .....	63
3.3.4 Wafer Bow Profile Measurement .....	64
3.4 Results and Discussion.....	64
3.4.1 Influence of Bonding Temperature on Bow Value .....	65
3.4.2 Residual Stress Through Thickness .....	68
3.4.3 Release Stress with Heat Treatment Method .....	69
3.5 MATLAB Software Development.....	71
3.6 Conclusion.....	74
<b>4. Characterization of Bonding Materials .....</b>	<b>77</b>
4.1 Anodic Bonding Material's Properties.....	77
4.2 Temperature-dependent CTE .....	79
4.3.1 Average CTE or Temperature-dependent CTE .....	80
4.3.2 CTE Measurement.....	81
4.3 Bonding Behavior of Bulk Bondable Materials.....	82
4.3.1 Bonding Mechanisms for Bulk Materials.....	83
4.3.2 Experimental Setup.....	83
4.3.3 Preparation and Cleaning of Pre-bonding Substrate .....	84
4.3.4 Bonding Configuration.....	87
4.3.5 Bonding Process .....	89
4.3.6 Bonding Results and Discussion.....	90
4.3.6.1 Bonding Ability at Different Temperatures and Voltages.....	91
4.3.6.2 Interface Inspection of Bonded Chips .....	91
4.3.6.3 Influence of Bonding Voltages .....	97
4.3.6.4 Influence of Bonding Temperature.....	98
4.3.6.5 Charge Transfer .....	100
4.4 Bonding Behavior of the Thin-Glass-Layer .....	101
4.4.1 Bonding Mechanisms for the Thin-Glass-Layer .....	102
4.4.2 Thin-Glass-Layer Deposition Method.....	102
4.4.3 Thin-Glass-Layer Characterization .....	105
4.4.3.1 Thickness Measurements .....	105
4.4.3.2 Quantitative WDX-analysis of Thin-Glass-Layer .....	106

4.4.4 Surface Quality of the Deposited Thin-Glass-Layer.....	108
4.4.5 Bonding Test .....	109
4.4.6 Bonding Prcess and Inspection .....	109
4.4.7 Bonding Results and Discussion.....	111
4.4.7.1 Influence of the Bonding Temperature .....	111
4.4.7.2 Influence of Bonding Voltage .....	112
4.5 Summary and Conclusion.....	113
<b>5. Residual Stress Modelling for MEMS.....</b>	<b>115</b>
5.1 Study of the Influence of Bonding Temperature, Material Property and Structure on the Off-set for Piezoresistive MEMS .....	115
5.2 Thermal Load to Residual Stress Issues.....	116
5.2.1 Material Date, Boundary Condition and Mesh.....	118
5.2.2 Simulation Results and Discussion.....	119
5.2.2.1 Influence of Bonding Temperature.....	121
5.2.2.2 Influence of Bonding Material.....	124
5.2.2.3 Influence of Bonding Structure .....	128
5.3 Pressure to Output Signal on MEMS.....	130
5.3.1 Background Equations and Estimation Process of a Membrane Structure .....	131
5.3.2 Model Definition .....	136
5.3.3 Material Date, Boundary Condition and Mesh.....	137
5.3.4 Simulation Results and Discussion.....	139
5.3.4.1 Maximum Displacement .....	140
5.3.4.2 Maximum Stress .....	141
5.3.4.3 Piezoresistive Effect and Outout Voltage .....	142
5.4 Residua Stress to Outout Signal on MEMS .....	145
5.4.1 Model Definition .....	145
5.4.2 Material Date, Boundary Condition and Mesh.....	147
5.4.3 Simulation Results and Discussion.....	150
5.4.3.1 Influence of Bonding Temperature.....	150
5.3.3.2 Influence of Bonding Materials .....	151
5.3.3.3 Influence of Bonding Structures.....	153
5.6 Conclusion.....	154
<b>6. Application of Low Stress for Stress Sensitive MEMS.....</b>	<b>157</b>
6.1 Bonding Structures for MEMS Pressure Sensor.....	157
6.2 Fabrication Flow of MEMS Pressure Sensor .....	158
6.3 Fabrication of Structured Thin-Glass-Layer on Silicon Substrate .....	161
6.3.1 Summary of the Defects .....	164
6.4 Fabrication Glass Interposer in Pyrex <sup>®</sup> 7740 and SW-YY <sup>®</sup> .....	165
6.5 Anodic Bonding Prcoess .....	166
6.6 Results and Discussion .....	169
6.6.1 Optical Inspection .....	169

6.6.2 Offset Measurement.....	170
6.7 Conclusion .....	174
6.7 Contributions to Knowledge .....	174
<b>7. Summary and Outlook .....</b>	<b>177</b>
7.1 Summary of Works .....	177
7.1.1 Thermal Stress Issue in the Anodic Bonding Process .....	177
7.1.2 Bonding Materials Characterization.....	178
7.1.3 Residual Stress Modelling for Sensitive MEMS.....	179
7.1.4 Bonding Materials and Structure for Real MEMS Sensor .....	180
7.2 Future Research.....	181
<b>Bibliography.....</b>	<b>183</b>
<b>A Matlab Code .....</b>	<b>191</b>
<b>B Roughness Measurement Results for Thin-Glass-Layer.....</b>	<b>219</b>
<b>C Fabrication Flow for Pressure Sensor .....</b>	<b>221</b>
<b>D Fabrication Flow for Silicon Substrate.....</b>	<b>225</b>
<b>E Offset Measurement Value .....</b>	<b>227</b>
<b>F List of Publications .....</b>	<b>229</b>
<b>List of Figures.....</b>	<b>236</b>
<b>List of Tables .....</b>	<b>238</b>