



# Contents

<b>Summary</b>	<b>v</b>
<b>Zusammenfassung</b>	<b>vii</b>
<b>Acknowledgements</b>	<b>xi</b>
<b>1 Vertical Integration of High-Performance Processor-Memory Stacks: Motivation &amp; Conception</b>	<b>1</b>
1.1 Driving Forces and Enabling Technologies . . . . .	1
1.1.1 Performance Benefits of Vertical Area Array Electrical Interconnects . . . . .	1
1.1.2 Enabling Technologies: Vertical Interconnects - Substrate Thinning - Alignment & Bonding . . . . .	3
1.1.3 Vertical Integration Product Roadmap . . . . .	6
1.2 Thermal Management Concepts and Limitations . . . . .	7
1.2.1 Power Dissipation Characteristics of IC-Dies . . . . .	7
1.2.2 Thermal Response of IC-Dies . . . . .	8
1.2.3 Established Heat Removal Concepts . . . . .	9
1.2.4 Back-side Heat Removal Limits of Vertical Integrated Chip Stacks . . . . .	10
1.2.5 Interlayer Thermal Management . . . . .	12
1.3 Convective Interlayer Heat Removal - a Scalable Concept . . . . .	12
1.3.1 Implementation Concepts: Via Sealing and Pressure Balanced Package . . . . .	13
1.3.2 Internal Flow Heat Transfer Characteristics: a Sensitivity Analysis at constant Geometrical Ratio . . . . .	14
1.3.3 Modular Heat and Mass Transfer Building Blocks . . . . .	17
1.3.4 Electro-Thermal Co-design / Optimization Framework . . . . .	22
1.4 Scope and Organization of the Thesis . . . . .	22
<b>2 Multi-Scale Modeling with Porous-Media Approach for Heat and Mass Transfer Design</b>	<b>25</b>
2.1 Detailed Conjugate Heat and Mass Transfer . . . . .	25
2.1.1 Fluid Flow Basics of NEWTONIAN Viscous Media . . . . .	25
2.1.2 Heat Conduction and Energy Conservation . . . . .	26
2.1.3 Limitations of Detailed Chip Stack Modeling . . . . .	27
2.2 Multi-Scale Modeling: Heat and Mass Transfer in Porous Media . . . . .	27
2.2.1 Volume Averaging of Porous Media . . . . .	28
2.2.2 From DARCY Flow to the Extended NAVIER-STOKES Equation . . . . .	29
2.2.3 Heat Transfer through a Porous Medium . . . . .	30
2.2.4 Porous - Solid Domain Interaction . . . . .	30
2.2.5 3D Solid to 2D Porous Media Field-Coupling . . . . .	32
2.3 Parameter Extraction from Efficient Sub-Domain Modeling with Periodic Boundary Conditions . . . . .	35
2.3.1 Sub-Domain Model using Periodic Boundary Conditions . . . . .	37
2.3.2 Parameter Set of Individual Heat Transfer Geometries in Symmetry Direction . . . . .	41
2.3.3 Parameter Set for Pin-Fin Arrays at Arbitrary Angle-of-Attack . . . . .	48
<b>3 Eutectic Bonding, Test Cavities, and Experimental Apparatus for Characterization</b>	<b>61</b>
3.1 Eutectic AuSn 80/20 Thin Film Bonding: Low Thermal Resistance, Leak Tight Interface . . . . .	61
3.1.1 Solder Technologies for Structural and Thermal Interfaces . . . . .	61
3.1.2 Formic Acid Assisted Thermo-Compression Bonding . . . . .	64
3.1.3 Thin Film Solder Bond-Line Formation . . . . .	66
3.1.4 Thermodynamic Stability of Under Bump Metallizations . . . . .	69
3.1.5 Solder Process Qualification . . . . .	72
3.2 Water Coolant Compatible Multi-Metal Layer System . . . . .	75
3.3 Single-Cavity, Double-Side Heated Test Vehicle . . . . .	78
3.3.1 Test Vehicle with Uniform Power Dissipation and Heat Transfer Geometry . . . . .	78
3.3.2 Test Vehicle with Non-Uniform Power Dissipation and Heat Transfer Geometry . . . . .	79



## Contents

3.4	Multi-Cavity Test Vehicle: Pyramid-Chip-Stack . . . . .	81
3.5	Single-Phase Test Loop with Spatially Resolved Infrared Imaging . . . . .	83
<b>4</b>	<b>Experimental Results and Validation of Modeling Framework</b>	<b>85</b>
4.1	Uniform Single Cavity Experiment: Unit-Cell Shape Efficiency . . . . .	85
4.1.1	Experimental Sequence and Extrapolation of Datasets . . . . .	86
4.1.2	Hydrodynamic Characteristics of Unit-Cells . . . . .	88
4.1.3	Heat Transfer Characteristics of Unit-Cells . . . . .	92
4.1.4	Flow Transition Augmented Heat Transfer . . . . .	95
4.1.5	Performance at Pressure or Pumping Power Constraints . . . . .	95
4.2	Non-Uniform Single Cavity Experiment to Validate Multi-Scale Concept . . . . .	99
4.2.1	Hydrodynamic and Spatially Resolved Thermal Measurements . . . . .	100
4.2.2	Field-Coupled Porous Media Model Representing Non-Uniform Cavities . . . . .	102
4.2.3	Validation of Multi-Scale Concept with Detailed Conjugate Heat and Mass Transfer Model of the Parallel Plate Test Vehicle . . . . .	102
4.2.4	Validation of Multi-Scale Modeling Concept with Experimental Results . . . . .	104
4.3	Thermally Communicating Fluid Cavities: Interlayer Cooled Pyramid Chip Stack . . . . .	111
4.3.1	Field-Coupled Porous Media Model Representing Pyramid-Chip-Stack . . . . .	111
4.3.2	Validation of Multi-Scale Modeling Concept with Experimental Results . . . . .	112
4.3.3	Tier-to-Tie Thermal Crosstalk . . . . .	113
4.3.4	Benchmarking of Fluid Delivery Architecture: Two-port vs. Four-port . . . . .	116
<b>5</b>	<b>Interlayer Cooling Design-Rules, Conclusions and Outlook</b>	<b>117</b>
5.1	Interlayer Cooled Chip Stacks: Performance and Characteristics . . . . .	117
5.1.1	Benchmark: Uniform, Two-port Interlayer Cooling vs. Back-Side Heat Removal . . . . .	117
5.1.2	Fluid Manifold Design: Pressure Penalty and Mass Flow Maldistribution . . . . .	118
5.1.3	Critical Hot-Spot Dimension: Hot-Spot Temperature Mitigation by Heat Spreading in Thin Dies	119
5.1.4	Thermal Transients: Time Constant and Retardation . . . . .	120
5.2	Advanced Interlayer Cooling: Design-Rules and Recommendations . . . . .	122
5.2.1	Unit-Cell Shape Menu and Interlayer Cooling Performance Scaling at Uniform Heat Flux . . . . .	122
5.2.2	Power Map aware Heat Removal: Heat Transfer Structure Modulation - Fluid Focusing - Fluid Delivery Architectures - Tier-to-Tier Crosstalk . . . . .	123
5.2.3	Electro-Thermal Co-Design: Interlayer Cooling Aware Floorplanning . . . . .	124
5.2.4	Interlayer Cooling Performance Evolution . . . . .	125
5.3	Future Research Agenda . . . . .	126
5.3.1	Interlayer Cooling Implementation: Reliable Packaging Technology . . . . .	126
5.3.2	Advanced Heat and Mass Transfer . . . . .	127
5.3.3	Extended Modeling Frame Work . . . . .	127
<b>A</b>	<b>Power Map Contrast specific Pin Shape Optimization</b>	<b>129</b>
A.1	Advanced Pin Shapes . . . . .	129
A.2	Pin Shape Selection with Respect to Power Map Contrast . . . . .	131
<b>B</b>	<b>Implementation of Porous-Media and Field-Coupling: ANSYS CFX</b>	<b>135</b>
B.1	Definition File Manipulation: CFX Command Line . . . . .	135
B.2	Mass Transport in the quasi Two-Dimensional Porous Domain . . . . .	135
B.3	Heat Transfer by Porous Domain Field-Coupling . . . . .	137
<b>C</b>	<b>Abbreviations</b>	<b>139</b>
<b>D</b>	<b>List of Symbols</b>	<b>141</b>
	<b>Bibliography</b>	<b>145</b>
	<b>List of Publications</b>	<b>153</b>