TECHNOLOGY REPORT

Current Developments in 3D Packaging With Focus on Embedded Substrate Technologies

PSMA 3D Power Packaging Phase II
A Special Project of the
PSMA Packaging Committee

March 2015

ISBN 978-0-9915644-4-6 (for Hard Copy)

ISBN 978-0-9915644-5-3 (for Soft Copy)

Authors:

LTEC Corporation
Louis Burgyan
Yuji Kakizaki
Yukata Hama
Hideki Nakagawa

Anagenesis, Inc.
Arnold Alderman

Fraunhofer-Institute for Reliability and Microintegration
Lars Böettcher
Thomas Löher

Copyright ©2015 PSMA. All Rights Reserved.

Table of Contents

Purpose of PSMA i

PSMA Mission i

Forward ii

Disclaimer ii

Acknowledgements iii

Table of Contents 1

Executive Summary 6

Introduction **10**
The Power Electronics Industry and the Energy Challenge 11
References 14

CHAPTER 1 EMBEDDING IN PCBS AND INORGANIC SUBSTRATES **16**

Embedding in PCBs **16**
Introduction 16
Component Embedding, Medium to High Density 19
Standards 22
The Elements of Component Embedding 23
Examples of Component Embedding and Package-integrated Modules 26
Component Embedding at AT&S (low power, medium density) 27
General Electric's Power Overlay (POL) Technology 31
Infineon's DrBlade™ Process 34
Power Modules at Schweizer Electronic AG. 35
Package-integrated Power Modules at Semicron 37
Shinko Electric Embedded Package Technologies 39
Fujikura's Wafer and Board-level Embedded (WABE} Process 41
Wurth Electronik's Embedded Component Technology (ECT) [1-34] 43
Andus Electronic Gmbh: Embedded Cu bars 44
Embedded PCB Manufacturers 44
European Research Activities 45

Embedding in Inorganic Substrates **48**
Introduction 48
Low Temperature Co-fired Ceramics (LTCC) for Passive Components Embedding 49
LTCC Ferrite Inductors 51
The weak points of Low Profile Lateral Flux LTCC Inductors 55
Non-LTCC Low-profile Lateral Flux Inductors 55
LTCC Technology Literature Review 59
LTCC/HTCC Material Suppliers and Foundries 61
Low-Cost Direct Bonded Aluminum (DBA) Substrates 61
Silicon Carbide Substrate/Interposer 63
Suppliers and Foundries of Inorganic Substrates. 64
Disruptive Technologies in Component Embedding 65
Organic and Inorganic Substrates Patent Landscape 66

Copyright ©2015 PSMA. All Rights Reserved.

Organic and Inorganic Substrates, Top Ten Assignees 66
Technology Influence Map 67
Organic Substrates Technology Roadmap 68
Technology Roadmap, Inorganic Substrates 69
Converging Packaging and Embedding Technologies 69
Summary and Conclusions 70
High Density, Low Power Embedding Technologies 71
Embedding Power Semiconductors 72
LTCC Technology in Power Electronics 73
References 73

CHAPTER 2 HIGH TEMPERATURE DIE-ATTACH AND HIGH-LEAD SOLDER SUBSTITUTION 79

Introduction 79
Material and Process Classification 80
Die-attach Methods for Power Semiconductor Devices 81
Silver Paste Sintering Methods 82
High-temperature Die-attach Research and Development at Osaka University 84
Zn Die Attach 85
Ag Sintering below 280 °C 85
Ag Sintering Using SiC Submicron Particle Dispersion 86
Stress Mitigation Bonding (SMB) Using Heat Flash 87
Additional Cited Research Papers 88
Transient Liquid Phase (TLP) Bonding and Diffusion Soldering 91
Electroplating as Die-attach Method 95
High-lead Solder Substitution Die-attach Methods 95
The DA5 Project (European Union) 96
The HotPowCon (HPC) Project 100
One-step Chip-attach Materials (OSCA) for Conventional Mass Reflow Processing 104
Patent Landscape 110
Technology Influence Map 111

Summary and Conclusions 115

References 116

CHAPTER 3 THERMAL MANAGEMENT 119

Introduction 119

Suppliers 120
Advanced Cooling Solutions Motivated by DARPA Initiatives 123
Thermal Ground Planes and Vapor Chambers 126
DARPA's Microtechnologies for Air-Cooled Exchangers (MACE) Program (2008-2012) 133
Research and Development During and After the MACE Program 133
The Nano Thermal Interfaces (NTI) Program 135
Research and Development During and After the NTI Program 136
Additional Research Papers 137
DARPA's Active Cooling Modules (ACM) Program 138
Pumped Two-Phase Cooling Systems 139
DARPA's Near Junction Thermal Transport (NJTT) Program and Follow-on Research 145
DARPA's Intrachip/Interchip Enhanced Cooling (ICECool) Program and Follow-on Research 146
Immersion Cooling 146
Vaporizable Dielectric Fluid Cooling of IGBT Power Semiconductors for HEV and EV Vehicle Powertrain Inverters 147

Copyright ©2015 PSMA. All Rights Reserved.

Application of Conduction-cooled PCBs and Composite Housing Materials in an Aerospace Electronic System ... 149
Constraining Core Stablcor® Laminate Inserts for PCBs and Substrates in Industrial and Consumer Applications ... 150
Standards ... 153
Technology Influence Map ... 153
Technology Roadmap ... 154
Patent Landscape ... 155
Summary and Conclusions ... 156
References[3-1] M. P. Mills, "The Cloud Begins with Coal," August, 2013. Link: http://www.tech-pundit.com/wp-content/uploads/2013/07/Cloud_Begins_With_Coal.pdf?c761ac ... 157

CHAPTER 4 PACKAGING TECHNOLOGIES ... 162
Introduction ... 162
Low-power 3D integration Enables Power Electronic Device Packaging ... 166
Power Electronic Packaging Platforms ... 166
Leadframe–based Discrete Semiconductors, ICs and Power Modules ... 169
Molded and Embedded Packages ... 170
Packaging Using Inorganic Substrates ... 172
High Power Hybrid Modules Using Inorganic Substrates ... 173
Application Examples ... 174
IGBT Module for Automotive Application, Oak Ridge National Laboratory ... 177
SiC Module for Automotive Application, Oak Ridge National Laboratory. ... 178
PoP Structures ... 180
Through – Mold Vias for Thermal Management and EMI Shielding ... 181
2.5D and 2.1D Integrated Modules ... 183
Additional Research Papers ... 184
Panel Based Packaging Technologies ... 186
OSATs ... 187
Patent Landscape ... 189
Summary and Conclusions ... 191

References ... 192

CHAPTER 5 INTERPOSERS ... 195
Introduction ... 195
Overview of Vertical Interconnection Methods ... 195
Interposer Classification ... 197
Inorganic Interposers ... 198
Organic Interposers ... 204
Interposer suppliers ... 206
Patent Landscape ... 207
Technology Influence Map Interposers ... 209
Technology Road Map Interposers ... 210
Summary and Conclusions ... 210
References ... 211

CHAPTER 6 EMBEDDED RESISTORS ... 213

Prolog to Chapters 6, 7, and 8 ... 213
Types of embedded components ... 213
Standards ... 214

Copyright ©2015 PSMA. All Rights Reserved.

Termination Options 216
Barriers 217

Resistors 218
Materials 219
"Inserted" Embedded Resistor Sources 221
"Formed" Embedded Resistor Sources 225
Enabling Technologies 230
Standards 231
Thermal & Cooling Considerations 231
Power Level Considerations 232
Research Landscape 232
Institute Research 234
Trends 234
Summary and implications 234
Roadmap 235
References 235

CHAPTER 7 EMBEDDED CAPACITORS 237
Formed capacitor materials 238
Planar or Laminate Capacitors 238
Present Leading Discrete Suppliers 238
Present Laminate Leading Products 243
Enabling Technologies 248
Standards 249
Thermal and Cooling Considerations 250
Power Level Considerations 250
Research Landscape 250
Development Trends 255
Summary and Implications 259
References 261

CHAPTER 8 EMBEDDED MAGNETICS 263
Types of embedded inductor components 263
Presently available sources for embedded magnetics 264
Enabling Technologies 274
Barriers 275
Standards 275
Thermal and Cooling Considerations 275
Power Level Considerations 275
Research Landscape 276
Trends 283
Summary and implications 285
Roadmap 288
References 289

CHAPTER 9 ADDITIVE MANUFACTURING AND LASER FABRICATION 292
Introduction 292
Additive Manufacturing and Laser Fabrication 293
Examples of potential benefits in 3D printing for industrial applications 305
Examples of Recent Successes in Direct Manufacturing 305
Technology Influence Map 307

Copyright ©2015 PSMA. All Rights Reserved.

Technology Roadmap 308
Patent Landscape 309
Summary and Conclusions 311
References 312

CHAPTER 10 EPILOGUE 315
Summary 321
Reference 321

Conclusions 322
Market Drivers 322
Technology Highlights 323
Solutions 323
Gaps 324
Trends 325
Strategic Implications 326

APPENDIX 1: 3D EMBEDDED COMPONENTS SURVEY 327

Survey Construction 327
Survey Introductory Remarks 328

Selected of Survey Questions and Answers 329
Q2. Your Organization is? 329
Q3. In what power levels are you primarily interested? (You can check more than 1 power level) 329
Q4. What do you believe the motivation would be to use component embedding would be (drop down rank 1 (lowest) to 5 (highest)? (Note that due to rounding up, sum may be off by 1 count) 330
Q6. If you are a power electronics manufacturer, are you using passive components embedded in substrates in 3D packages? 330
13. Which technologies and materials do you believe will have impact on the parameters listed? Check off the impact you believe the technology or material will have on embedded capacitors in the appropriate parameter column. Multiple answers are allowed. 331
18. Choose the type of component you believe would be of interest to power converter manufacturers by indicating the time frame for that device being used in embedded ORGANIC substrates (printed circuit boards). (More than one selection is allowed.) 332
19. Choose the type of component you believe would be of interest to power converter manufacturers by indicating the time frame for that device being used in embedded INORGANIC substrates. (More than one selection is allowed.) 332
27. In your area of product development, do you foresee any need for interposers within the next few years? 332
35. Which of the following cooling methods are of interest to those involved in 3D embedded packaging? Please rank your level of interest on scale of 1 (lowest) to 5 (highest) for each method. 333
36. Does liquid cooling have a place in server farms? 333

Author Biographies 334

Copyright ©2015 PSMA. All Rights Reserved.