Significant Developments and Trends in 3D Packaging of Power Products

Presented by
PSMA Packaging Committee
Brian Narveson and Ernie Parker, Co-Chairmen

www.psma.com, power@psma.com
Technology Report Commissioned

- Why: Power industry is constantly being asked to deliver higher density (W/cm³) at lower cost with higher efficiency
- Methodology: Tyndall National Institute commissioned to create Technology Report through:
  - Research of published material from industry, government and academia
  - Interviews with Industry and Academic Experts
  - Attending trade shows and seminars
- Purpose: To determine the impact of 3D Power Packaging on power supply manufacturers and their supply chain
- Phase 1 report available now: Phase 2 in progress
What is 3D Power Packaging

• Power supply products derived from the use of the z axis
• Incorporation of a variety of technologies to reduce footprint
• Solutions that increase power density (W/cm³)
• Manufacturing solutions that can print or construct interconnects or circuit layers

Embedding Actives or Passives in Substrate

3D Stacked Die Packaging (Amkor)
Power Market Drivers

• Data Centers
  – 3% and growing of USA electricity*
  – 60 billion kWh *
  – Projected to double every 5 years *

• Servers
  – Low end servers at 1 kW with roadmap to 3-5 kW per board
  – High end servers at 10 kW with roadmap to 20-30 kW each compute drawer

• Mobile Devices
  – 1.8 billion mobile phones sold in 2013
  – Close to 1 billion smart phones sold in 2013
  – In 2014 the number of smart phones in use will surpass the number of PC’s
  – Gartner estimates Smartphone sales (units) to be 6X PC sales in 2017
  – 250 million tablets sold in 2013

• Mobile Phone Towers
  – 40 billion kWh *

IBM High End Server System

Each Compute Drawer Uses ~19 kW
Single Rack System Rated up to 235 kW
Part of The Compute Drawer

Top Side

Densely packaged with eight *QCMs and 128 DIMMs

*QCMs = Quad-core modules

Bottom Side
Cold Plate & TIM Removed

Power is N+2 redundant per voltage level per octant
192 total power converters
Why is 3D Packaging Important

- What you told us: feedback on what’s driving packaging challenges
Where will 3D Packaging be Important

- What you told us: survey results and how they relate to 3D Packaging

<table>
<thead>
<tr>
<th></th>
<th>0 - 10W</th>
<th>11 - 50W</th>
<th>50 - 250W</th>
<th>251 - 500W</th>
<th>501 - 999W</th>
<th>1KW+</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industrial</td>
<td>⭐⭐⭐⭐⭐</td>
<td>⭐⭐⭐⭐</td>
<td>⭐⭐</td>
<td>⭐</td>
<td>⭐</td>
<td>⭐</td>
</tr>
<tr>
<td>Military/Aero</td>
<td>⭐⭐⭐⭐⭐</td>
<td>⭐⭐⭐⭐</td>
<td>⭐⭐⭐⭐</td>
<td>⭐</td>
<td>⭐</td>
<td>⭐⭐⭐⭐</td>
</tr>
<tr>
<td>Smartphone/tablet</td>
<td>⭐⭐⭐⭐⭐⭐</td>
<td>⭐⭐⭐⭐</td>
<td>⭐⭐⭐⭐</td>
<td>⭐</td>
<td>⭐</td>
<td>⭐⭐⭐⭐</td>
</tr>
<tr>
<td>Server</td>
<td>⭐⭐⭐⭐⭐⭐</td>
<td>⭐⭐⭐⭐⭐⭐</td>
<td>⭐⭐⭐⭐⭐⭐</td>
<td>⭐</td>
<td>⭐</td>
<td>⭐⭐⭐⭐</td>
</tr>
<tr>
<td>PC</td>
<td>⭐⭐⭐⭐</td>
<td>⭐⭐⭐⭐⭐</td>
<td>⭐⭐⭐⭐</td>
<td>⭐</td>
<td>⭐</td>
<td></td>
</tr>
<tr>
<td>Comms</td>
<td>⭐⭐⭐⭐</td>
<td>⭐⭐⭐⭐⭐</td>
<td>⭐⭐⭐⭐</td>
<td>⭐</td>
<td>⭐</td>
<td></td>
</tr>
<tr>
<td>Consumer</td>
<td>⭐⭐⭐⭐</td>
<td>⭐⭐⭐⭐</td>
<td>⭐⭐⭐⭐</td>
<td>⭐</td>
<td>⭐</td>
<td></td>
</tr>
<tr>
<td>Transport/Auto</td>
<td>⭐⭐⭐⭐</td>
<td>⭐⭐⭐⭐</td>
<td>⭐⭐⭐⭐</td>
<td>⭐</td>
<td>⭐</td>
<td>⭐⭐⭐⭐</td>
</tr>
</tbody>
</table>

Identified DC-DC markets for 3D packaging
Disruptive Technologies

- Wide Bandgap Devices
  - High switching frequencies but need for very low parasitics (3D Packaging)
- Switched capacitor and high frequency resonant topologies
  - FINsix VHF switching up to 100 MHz with 3X-5X size reduction
- Cooling
- Emergence of embedding as a viable packaging alternative at all power levels
Technology Areas Studied

- Chip Scale
- PCB Scale
- High Power Modules (AC-DC & DC-DC)
- Additive Manufacturing
Chip Scale

• Examples of Chip Scale Products
  – Semiconductor packages with 3D lead frames
  – Packages including the inductive and capacitive components
  – Chip Scale packages with embedded components
  – Integration of air core inductors at the silicon level (Intel Haswell)

Intel Fully Integrated Voltage Regulation (FIVR)
Chip Scale Technologies

- Embedding in PCB

AT&S ECP process

TI’s MicroSiP™
Chip Scale Technologies

• Magnetic Substrates

Murata LXDC Series of Converters
# Chip Scale Roadmap

<table>
<thead>
<tr>
<th>Now &amp; Immediate</th>
<th>Likely Developments</th>
<th>Future Scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Chip scale POL</strong></td>
<td>Integrated magnetics (&lt;15A) (Enpirion)</td>
<td>Improved processes for low loss magnetic materials, higher freq operation.</td>
</tr>
<tr>
<td><strong>Integration with load</strong></td>
<td></td>
<td>Increasing current level (amps)</td>
</tr>
<tr>
<td>Integration with performance load (Haswell)</td>
<td>Flip chip POLs</td>
<td>Further penetration, subject to thermal limitations</td>
</tr>
<tr>
<td><strong>Embedded actives</strong></td>
<td></td>
<td>Majority of μProc, SOC will have power from single rail with in/on chip POL</td>
</tr>
<tr>
<td>TI pioneering with MicroSIP</td>
<td>New business model. Investment in supply chain &amp; qualification</td>
<td></td>
</tr>
<tr>
<td>Embedded actives in infancy</td>
<td>Vertical integration route for semi companies</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Merchants integrate best components</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Industry standards development</td>
<td>Support for design and qual from semi and passive suppliers</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SMT solns. displaced by embedded solns.</td>
</tr>
</tbody>
</table>
PCB Scale

- PCB assembly sometimes with overmolding

1/4 brick 60 W, 1992

1/4 brick, 860 W, 2014

Molded, 10 W, 1991

Molded, 1.2 kW, 2014
Innovations in “brick-type” power converters

- Stacking Quarter Bricks
Embedded Active Components

- Significant progress has been made through two EU Framework Programmes, “HIDING DIES” [FP6] and “HERMES” [FP7]
  - HIDING DIES developed the technology for embedding components
  - HERMES focused on commercialization of the technology
- TI’s MicroSIP is the 1st commercial dc-dc produced with HERMES ‘face down approach’
  - ROHM/TKDK created a 2nd source using SESUB process

Cross section of "SEmiconductor embedded in SUBstrate" (SESUB)
Embedded Active Components

- Example of HERMES face-down technology with two embedded core FR-4 PCBs, Prepreg layers, and external components

- Conceptual view of Crane Aerospace & Electronics embedded components in fusion bonded Multi-Mix® assembly; fusion bonding eliminates Prepreg layers

- Other embedding technologies available in the industry
  - Nanium's embedded wafer level package (eWLP)
  - Integrated Module Board (IMB) from Imbera
  - Amkor's Embedded Die/Passives in Substrate
  - SiPLIT from Siemens
  - DrBlade from Infineon
  - i2 Board®, p2 Pack® from Schweizer

[Diagram of embedded components]
PCB Scale Technologies

- Embedding passive components within Printed Circuit Boards

Integrated Filters

- Researchers at the Power Electronics Systems Laboratory at ETH Zurich have proposed 3D integrated passive and active EMI filters.

- The passive filter (left) achieved a 24% reduction compared to the discrete solution.
- The combination of active and passive solutions (right) achieved a 40% reduction.
Enhanced Cooling

A process developed for a mixed technology RF amplifier called an Integrated Thermal Array Plate (ITAP) shows promise for power electronics application. In this process ICs, passives, and semiconductor components are held on a temporary carrier and a metal heatsink is electroformed around them.
Overmolded Modules

An overmolded PWB based power module was previewed by Vicor at the APEC 2013 plenary

- A 380 V - 48 V unregulated bus converter released in Jan of 2014 is rated at:
  - 1.2 kW
  - 98% efficiency
  - 1820 W/in³

- Additional products release claimed to demonstrate up to 3 kW/in³

The overmolded packaging approach also provides 3D cooling benefits¹¹
Power packaging at the PCB scale is forecast to transition from SMT on FR4 to embedded technology.
Supply chain demand for compatible passives and magnetics
Thermal interface and cooling technology will become more integrated
High Voltage/Current Power Modules

• Applications
  – Industrial and Transportation Controllers
  – Power Inverters
  – IGBT Modules
  – Motor Drives
  – Harsh environment modules in terms of high voltage, high current, high temperature, vibration etc.

40kW E-Motor drive with embedded IGBTs and Diodes. Schweizer p² Pack®technology
High Power Module Technologies

• Embedding Actives and Passives
  – Embedded die attach with low pressure and low temperature sintering (EU project “HI-LEVEL”)
  – Schweizer p² Pack
  – Wire bond Replacement

• Mechanical and Thermal Interface Improvements
  – Sintering for Heat Sink Attach
  – Sintering for Die Attach
  – Sintering for Interconnect

• Functional Partitioning
High Power Module Technologies

- Embedding Actives and Passives

  - Schweizer p² Pack

p² Pack® module assembly with logic PCB

p² Pack® vs. DCB module, (courtesy Schweizer Electronic AG)
High Power Module Technologies

- Mechanical and Thermal Interface Improvements
  - Sintering for Interconnect

SKiN technology from Semikron

AC terminal
auxiliary terminals
IGBTs FWD
DC terminals

SKiN technology from Semikron
# High Power Module Roadmap

## Now & Immediate
- **Modules**: Wirebonding and solder die attach
- **Embedding**: Industrial demonstrators for IGBT in motor control to 40kW
- **Thermal**: Eutectic die attach
- **High current**: Multiple wirebonds

## Likely Developments
- **Modules**: Planar interconnect and sintering
- **Embedding**: Conventional solns. cede share to embedded PCB
- **Thermal**: Move to sintering
- **High current**: Connector design innovation

## Future Scenarios
- **Modules**: Fully embedded high power modules
- **Embedding**: Competitive to hybrid module solutions
- **Thermal**: Nano materials
- **High current**: Distributed conversion to lower voltage

---

**Note**: The diagram outlines the evolution and advancements in high power modules and associated technologies.
Additive Manufacturing

- Definition: Additive manufacturing implies the deposition of material in geographically distinct layers that build on each other to form a 3D part in contrast to general parts manufacturing which is often a subtractive process (drilling, milling, turning etc.).

- Relevance to power electronics
  - Prototyping of complex plastic and metal parts without the need for intermediate tooling
  - Rapid design iterations
  - Usage includes printed fan bezels, complex chassis parts, heat-sinks, bobbins, high current metal interconnect
Market Dynamics of Additive Manufacturing

• Metal and Plastic printing available now

• Machine cost decreasing and availability increasing while and material cost is plummeting
  – Entry level plastic machines now approaching $1000
  – Arburg just introduced a machine that uses standard granular materials used in injection molding

• Large number of quality materials available
  – Plastics including ADS (ES07, M30, M30i), ABSi, PC-ABS, Polycarbonate, PC-ISO, Ultem 9085, PPSF/PPSU plus rubber like and bio-compatible materials.
  – Metallic materials include Stainless Steel (GP1, PH1), Cobalt Chrome (MP1, SP2), Titanium, Nickel Alloy through Copper, Silver and Gold
Plastic Additive Manufacturing Technology

- Fused Deposition Modeling (FDM)

1 - nozzle ejecting molten plastic,
2 - deposited material (modelled part),
3 - controlled movable table

Metal Additive Manufacturing Technologies

- Aerosol Jet

Aerosol Jet Process

Optomec printing cell phone antenna on plastic
Additive Manufacturing Roadmap

• Detailed roadmap in the report

• Printer suppliers claiming breakeven cost with conventional technologies at 10 k – 25 k pieces

• Your competitors are using this technology to prototype plastic and metal parts in less time at lower cost

• The move from prototype to production is as simple as moving to a higher capacity printer

• Many job shops are available
Summary

• Significant move to integrate the POL in the same package as the load.

• Intel (Haswell) has proven volume integration of inductors in silicon.

• Viable embedded solutions where active and passive components are embedded into the PCB (ceramic or fiber) and Cu interconnect is plated onto the device terminations is in volume production now.

• Additive manufacturing in both metal and plastic is real. It will reduce development time and cost.

• Liquid cooling at the board and module level is being demonstrated.

• High frequency (>5 MHz) is coming but progress is slow on obtaining commercially available high frequency magnetic materials with low losses.
Next Step: Phase II

- Phase II will provide an in depth study of embedded 3D packaging
- Timeframe – May 2014 to March 2015
- Completion date for Phase 2 report – APEC 2015.
- Summary will be presented at APEC 2015 in the Industry Session 3D Power Packaging.
11. From APEC 2014 Industry Session IS 1.5 “3D Packaging for Power”, Vicor presentation on “3D Cooling of New High Density DC-DC Converters”