PASSIVE COMPONENTS FOR A 3D ENVIRONMENT

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Commercial Power Electronics - drawbacks

2D layout + Non-uniform height + Poor thermal properties =
= LOW POWER DENSITY

Mixed technology THT & SMT + “Odd shape” assembling parts =
= LABOUR INTENSIVE MANUFACTURING

PE examples – commercial products

2.2kW Industrial drive

150W HID Lamp
Electronic ballast

Labour intensive construction

Labour cost:
China: < $1/hr
U.S.: $16/hr

Source: CPES/Darnell

Power Supplies for personal computers

Made in US
100%
50%

Year
Outline

- Background ✓
- Power Sandwich concept for manufacturability
- X-dim Components
- Automated manufacturing
- Multilayer Thermal Management Concept
- Natural Convection demonstrator
- Forced air Cooling demonstrator
- Conclusion
Power Sandwich concept for manufacturability

- **X-dim components**
  - Uniform (or compatible) height – x=14mm
  - Double sided SMT components
  - Enhanced thermal properties

- **Power Sandwich system integration**
  - Double sided and multi-layer soldering
  - Components active in the heat removal from each others
  - 3D loss density dependent components arrangement

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**Loss density dependent arrangement**
- Medium loss density
- Low loss density
- High loss density
Power Sandwich Case Studies

150W HID Lamp Electronic Ballast
- Power Density Increased by 2X
- Footprint reduced by 3.4X (Important for ballasts)

2.2KW Inverter for Motor Drive
- Power Density Increased by 3.8X
- Very Simple Thermal Management

Standard (0.46 kW/l) VS Power Sandwich

Standard Power Sandwich

Power Sandwich (1kW/l)

Standard

Power Sandwich

Big Heat Sinks

No typical heat sinks

1kW/l

3.8kW/l

150W HID Lamp Electronic Ballast

2.2KW Inverter for Motor Drive

Standard

Power Sandwich

1kW/l

3.8kW/l
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X-dim Components Samples – **Inductors**

- Drum and shield construction, $x=14\text{mm}$
  - Reduced packaging - No coil formers
  - Double sided SMT

- **Thermal performance improvements**
  - Integrated SMT tabs
  - Potting

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**Construction parts**
- **Drum**
  - 23 mm
- **Shield**
  - 26 mm
- **Cu SMT tabs**

**Inductor Samples**
- **X=14mm**
  - $L=240\mu\text{H}$

**Standard vs. X-dim**
- (L=240\mu\text{H}, $I_{\text{max}}=4\text{A}$)
  - Standard 14100mm³
  - X-dim 9460mm³
  - Vol. reduced by ~30%.
X-dim Components Samples – Inductors Thermal Performance

- Temperature rise measured at two points in the winding
- Low $\Delta T$ (max 3.8°C) in x-dim inductor.

![Measurement points](image1)

![Experimental set-up](image2)

$\Delta T_2 = 3.8°C$

$\Delta T_1 = 3.1°C$

Heat sink (Al)+kapton+TIM Interfaces equivalent to the real assembly
X-dim Components Samples – Capacitors

**METAL-FILM CAPACITORS, 14mm**
- TM stress relieves
- Reduced packaging, vertical film orientation

**Thermal behavior**

- Symbols: thermally enhanced, standard
- Graph showing temp rise in capacitor [K] vs Q1[W], Q2=0:
  - R<sub>th horiz</sub>
  - R<sub>th vert</sub>

**Construction**
- TM stress relieves
- LCP packaging

**Samples**
- Bare & Vertical-film
- Boxed Cu SMT tab
- X= 14 mm

**ELECTROLYTIC CAPACITORS, 1.5X**
- Axial leaded double sided construction
- Teflon sleeve

**Construction**
- Winding body
- A tab
- C tab

**Samples**
- Double sided
- Single-sided (alternative)
- Teflon case
- Double sided
- Teflon case
- 1.5X=21mm
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Power Sandwich SMT automated manufacturing features

- Multilayer SMT assembly and stacking
  - Gluing x-dim components to the PCB, P&P x-dim components, P&P of populated substrate
- Double sided soldering
  - Solder paste application on PCBs and x-dim components, Soldering of x-dim components from top and bottom
- Multilayer soldering
  - Double sided soldering in a few stack layers, Soldering different thermal capacitances
Power Sandwich - process flow/manufacturing sections

- **Components assembly**
  - Components assembled on single substrates (Similar to standard SMT assembly)
- **Layers stacking and soldering**
  - P&P populated substrates, Double-sided and Multi-layer soldering

Components assembly

START → Apply solder paste and glue on PCBs → P&P x-dim components → Glue curing → END

Apply solder paste on x-dim components → P&P populated PCBs - stacking → Vapour-phase soldering → Cleaning, inspection → END

Layers stacking and soldering

Cleaning, inspection

Components assembly

Layers stacking and soldering
Power Sandwich – application of attachment media

- Stencil printers, screen printing
- The same height of x-dim components → screen printing on x-dim components enabled
- Double sided x-dim components → the same stencil used for substrates and x-dim components
Power Sandwich – Pick and Place

- Vacuum nozzles for P&P
- Coo-planarity inherent to Power Sandwich → P&P of populated substrates enabled (by vacuum nozzles)
Power Sandwich – Soldering

- Soldering large and different thermal capacitances (X-dim vs. standard SMT)
- Solution:
  - Enable faster temperature response of the components
  - Enable more uniform heat distribution
  - Limit maximum temperature (overheating)

Temperature profiles - Simulation results

With the vapour-phase ovens, greater and more uniform heat transfer results in smaller temperature difference between small and large thermal capacitances (2°C at peak temperature)!
Power Sandwich – Soldering experimental results

- Temperature rise experiments on X-dimension components

- Temperature rise experiments on X-dimension assembly

Temperature-time profiles during soldering of CM choke and 4 metal-film capacitors on two sides and 2 metal-film capacitors on one side with assembly preheated at 45mm above minimum position in the oven.
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Multilayer Thermal Management Concept – Power Sandwich

3D multilayer thermally conductive structure
Structure carries thermo-mechanical stresses
PCBs and IMSs spaced by Cu tabs soldered at both sides
Empty spaces for adding functionality

Circuit functionality
Semiconductors and passive components
Cu SMT tabs: mechanical, thermal, electrical

X-dim components
Integrated Cu tabs – double sided SMT
Compatible in height (x) & Thermally enhanced
Multilayer Thermal Management Concept – Power Sandwich

- **Multi-sided Cooling**
  - Heatflow to more surfaces
  - X-dim components participate in heat exchange between layers

- **X-dim Components Contribution**
  - Reduce $R_{th}$ inside converter
  - Facilitate more uniform $T$ in the system

\[ R_{th_x} \ll R_{th_hs} \]

**Natural Convection**

\[ R_{th_x} \ll R_{th_hs} \]

**Forced Convection**

\[ R_{th_x} \approx R_{th_hs} \]

Smaller heat sinks to keep components below specified limits

X-dim components
Multilayer Thermal Management Concept – Thermal Cycling

- EMI filters with standard passive components and Power Sandwich EMI filter with x-dimension components used in temperature cycling experiments.

Initial thermal cycling tests did not reveal component destruction and failure of solder joints.

After 900 temperature cycles single- and doublesided soldering of SMT x-dimension components did not shown weakness.
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Temperature Distribution Analysis – Natural Convection

- Power Sandwich HID Ballast Case Study
  - 3-layers assembly
  - Total power loss $P=9\text{W}$
  - Real power loss distribution: $P_{\text{top}}=4.2\text{W}$, $P_{\text{bot}}=4.8\text{W}$

- Find Temperature Distribution for Two Cases by CFD Simulations
  - Nearly the same (real) power loss distribution at top and bottom: $P_{\text{top}}=4.2\text{W}$, $P_{\text{bot}}=4.8\text{W}$
  - Different power loss distribution at top and bottom: $P_{\text{bot}}=2P_{\text{top}}$; $P_{\text{bot}}=6\text{W}$, $P_{\text{top}}=3\text{W}$

3D Layout Case Study

Bottom layer
- X-dim inductor
- Cu SMT tabs

Bottom + middle layer
- X-dim capacitor

Sandwich HID Ballast
- Bottom + middle + top layer
- $P_{\text{top}}$
- $P_{\text{mid}}=0\text{W}$
- $P_{\text{bot}}$
Temperature Distribution Analysis – Natural Convection

- CFD Modeling Steps
  - Create equivalent 3D Copper Reinforced Structure
  - Add components exhibiting power loss, no loss in the middle (EMI filter components)
  - Add 2 U-profile heat sinks covering 4 sides
  - Add isolation layers from sides not active in heat removal
Natural Convection Cooling – Thermal Design

- 150W HID Lamp Electronic Ballast
- 4-sided heat removal concept

Thermal Management Method
Natural Convection Cooling – Modeling Results

- **Optimized heat sink model**
  - natural convection + radiation
  - \( 2P_{\text{heat-sink}} = 6.2 \text{W} \)

- **Vertical plate model**
  - natural convection + radiation
  - \( 2P_{\text{plate}} = 2.8 \text{W} \)

- **Total power**
  - \( P_{\text{total}} = 9 \text{W} \)
Natural Convection Cooling – **Modeling Results Summary**

**Stacked buck x-layer**

- Ambient temperature $T_a = 55^\circ C$
- Heat Sink temp: $T_{h\text{-sink}} = 100^\circ C$
- X-dim Component temp: $T_{x\text{-dim}} = 103^\circ C$

Compared to the state of the art construction power density is increased by factor of 2 (0.9kW/l)

**Stacked buck & Low loss density x-layers**

- Height: 14mm

$0.9\text{kW/l}$

(2x)
Natural Convection Cooling – Experimental Results

Ambient temperature $T_a = 22^\circ C$
Power Sandwich vertical orientation
The temperature at IMS uniform at $70^\circ C$
$\Delta T$ in x-dim components low

HID Ballast Thermal Image (after 3 hours)

Heat Sink Model Verification

$P = 9.6 W$ for $\Delta T = 23.5^\circ C$ and $n_{fj} = 15 \Rightarrow error +4\%$

$Q = 10 W \Rightarrow \Delta T = 23.5^\circ C$
$w = 158 mm$

$P(n_f)$

$P(n_f)$

$P(n_f)$

$n_f = 15$

$100 mm$
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Forced Convection Cooling - Concept

- 2.2kW Inverter for Motor Drive with SiC JFETs
- Heat sources separated at two sides
  - Rectifier top side
  - Inverter bottom side
- High density packaging of x-dim passives
  - Low power loss

Double-sided Heat Removal &
Low Power Loss of SiC Inverter

GOAL: No Use of typical Heavy/Complex Heat Sinks
Forced Convection Cooling – **Spatial Design**

- Loss density dependent components packaging
- 2-layers power sandwich assembly

Assembly steps

1. SiC inverter
2. Control board
3. EMI filter
4. Rectifier

SMT Sub-assemblies
Forced Convection Cooling – Thermal Design & Modeling Results

- Thermal Management Optimization
  - Fan selection
  - Independent channel heights \((s_1, s_2)\) adjustment

![Diagram showing flow rate and pressure rise with channel heights](image)

Optimal channel height \(s_1=4\text{mm}\) yielding the highest heat transfer coefficient \(h\approx70 \text{ W/(m}^2\cdot\text{K)}\)

Compared to the state of the art construction power density is increased by factor of 3.8 \((3.8\text{kW/l)}\)
Forced Convection Cooling – Experimental Results

3.8kW/L (3.8X)

Ambient temperature $T_a = 22^\circ C$
Heat Sink temp: $T_{h\text{-sink}} = 44^\circ C$
Components: $T_{comp} < 50^\circ C$

THERMAL MEASUREMENTS

IR Image (SiC Inverter Channel)

Measured T of Al plates (SiC Inverter)

- Al plate 2
- Al plate 1

THERMAL COUPLES
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• Power Sandwich technology benefits
  • PCB based
  • Standardised SMT components
  • Automated assembly
  • Effective thermal management
  • High density packaging

\[
\text{Cost} \quad (\text{component & assembly})
\]

\[
\text{High power density}
\]