

Application of the PCB-Embedding Technology in Power Electronics

State of the Art and Proposed Development

Cyril BUTTAY¹, Florent MOREL¹, Christian MARTIN¹,
Rémy CAILLAUD², Johan LE LESLE², Roberto MRAD²,
Nicolas DEGRENNE², Stefan MOLLOV²

¹Laboratoire Ampère, Lyon, France

²Mitsubishi Electric Research Centre Europe, Rennes, France

27/6/18

Introduction

State of the Art of PCB embedding

Proposition – Design Tools for Power Electronics

Conclusions

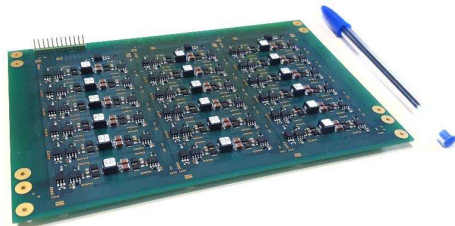
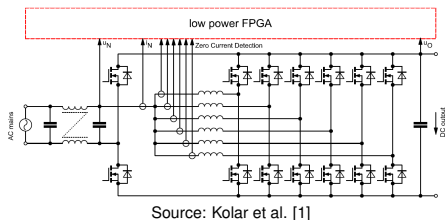
Introduction

State of the Art of PCB embedding

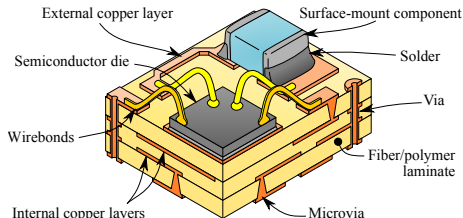
Proposition – Design Tools for Power Electronics

Conclusions

Power electronics – Areas for Progress



- ▶ Excellent active devices are now available (SiC, GaN)
- ▶ Many topologies introduced over the years;
 - ▶ Recent changes: multicellular structures
- ▶ Integration and Packaging are the main areas for progress
 - ▶ Reduce size and circuit parasitics, improve thermal management. . .
 - ▶ Manage increased interconnexion density



Printed Circuit Board is

- Mature**
- ▶ Large range of available design software
 - ▶ Can be manufactured in large quantities, low price
 - ▶ Mainly oriented towards microelectronics and low power

- Flexible**
- ▶ Custom design
 - ▶ Many configurations possible

- Limited**
- ▶ Poor thermal conductivity

Introduction

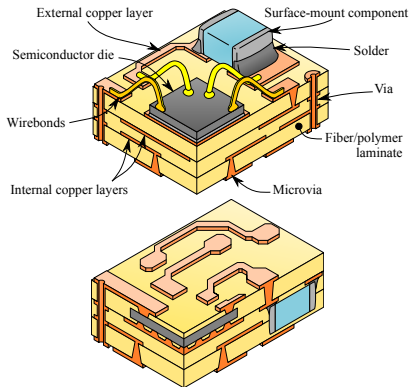
State of the Art of PCB embedding

Proposition – Design Tools for Power Electronics

Conclusions

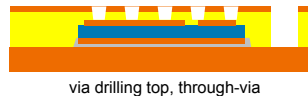
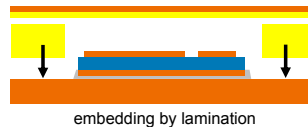
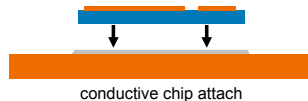
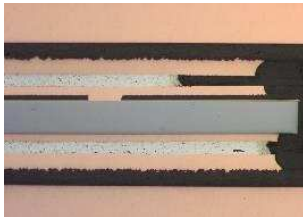
Why Embedding?

- ▶ Optimize thermal management
 - ▶ Heat sources closer to heatsink
 - ▶ Dual side cooling
- ▶ Improve performance
 - ▶ Shorter interconnects
 - ▶ Lower inductances
- ▶ Reduce size
 - ▶ Use substrate volume
- ▶ Manage complex interconnects
 - ▶ Batch process



Embedding of Power Dies – 1

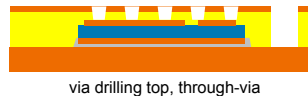
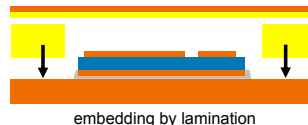
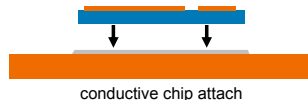
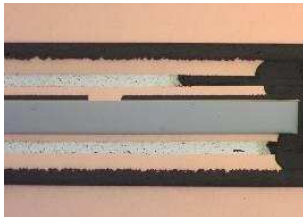
- ▶ Most embedding effort on power dies:
 - ▶ Most power density
 - ▶ Fastest voltage/current transients
- ▶ Requires special finish on dies
 - ▶ 5-10 μm Cu (not standard)
 - ▶ Buffer for UV laser
 - ▶ Also for microetch in plating step
- ▶ Backside connexion by sintering or vias
 - ▶ Sintering compatible with standard dies
 - ▶ Vias require Cu finish and adhesive



Left and above, source: Ostmann [3]

Embedding of Power Dies – 1

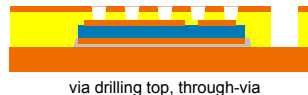
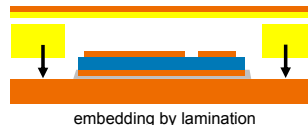
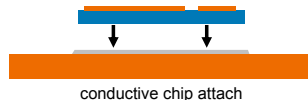
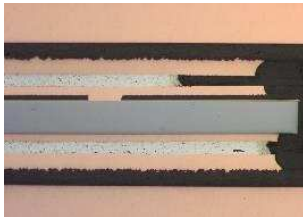
- ▶ Most embedding effort on power dies:
 - ▶ Most power density
 - ▶ Fastest voltage/current transients
- ▶ Requires special finish on dies
 - ▶ 5-10 μm Cu (not standard)
 - ▶ Buffer for UV laser
 - ▶ Also for microetch in plating step
- ▶ Backside connexion by sintering or vias
 - ▶ Sintering compatible with standard dies
 - ▶ Vias require Cu finish and adhesive



Left and above, source: Ostmann [3]

Embedding of Power Dies – 1

- ▶ Most embedding effort on power dies:
 - ▶ Most power density
 - ▶ Fastest voltage/current transients
- ▶ Requires special finish on dies
 - ▶ 5-10 μm Cu (not standard)
 - ▶ Buffer for UV laser
 - ▶ Also for microetch in plating step
- ▶ Backside connexion by sintering or vias
 - ▶ Sintering compatible with standard dies
 - ▶ Vias require Cu finish and adhesive

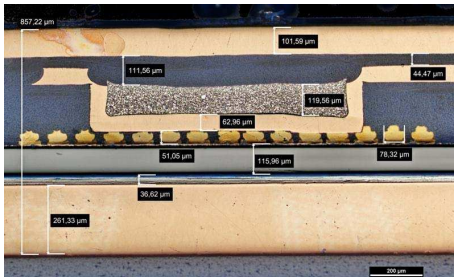


Left and above, source: Ostmann [3]

Embedding of Power Dies – 2

Some alternative techniques

- ▶ Stud bumps and machining
- ▶ Foam interposer
- ▶ Mechanical drilling

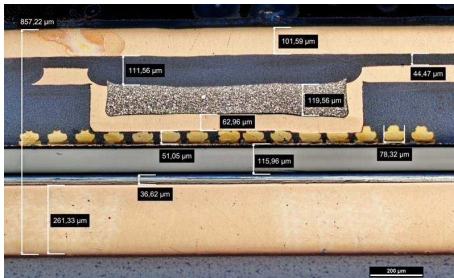


Source: Hoene et al. [4]

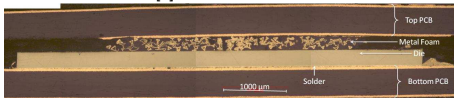
Embedding of Power Dies – 2

Some alternative techniques

- ▶ Stud bumps and machining
- ▶ Foam interposer
- ▶ Mechanical drilling



Source: Hoene et al. [4]

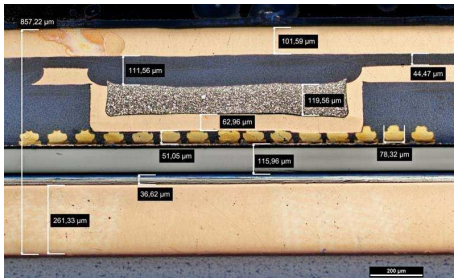


Source: Pascal et al. [5]

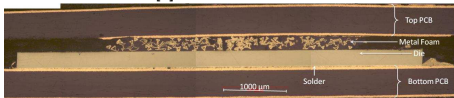
Embedding of Power Dies – 2

Some alternative techniques

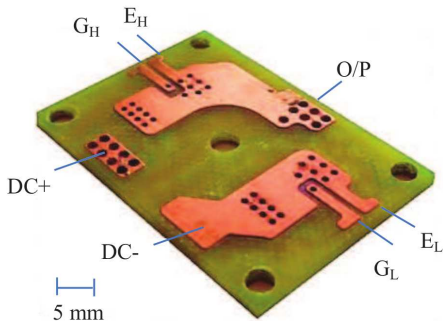
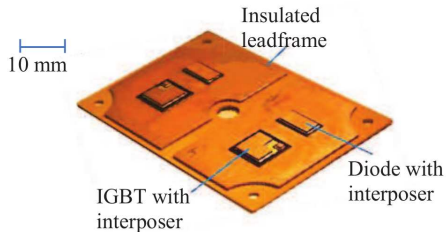
- ▶ Stud bumps and machining
- ▶ Foam interposer
- ▶ Mechanical drilling



Source: Hoene et al. [4]

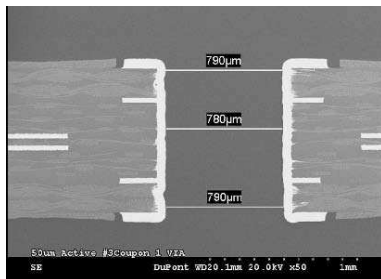


Source: Pascal et al. [5]

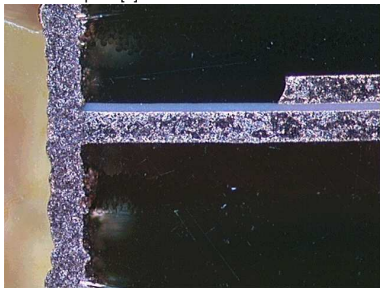


Source: Sharma et al. [6]

Embedding of Formed Components – Capacitors



Source: Dupont [7]



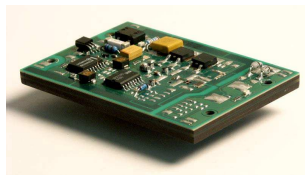
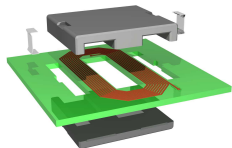
Source: Andresakis [8]

- ▶ introduction of a capacitive layer in the stack-up
 - ▶ thin layer (8–25 µm)
 - ▶ high permittivity (e.g. BaTiO₃ filler)
- ▶ single layer plane capacitor
- low capacitance density
- limited voltage strength
 - ▶ $\approx 1 \text{ nF cm}^{-2}$ for 100 V rating
- more suited to GHz-range decoupling than to power electronics

Embedding of Formed Components – Inductors

Magnetic Layer

- ▶ Relies on magnetic/polymer film \rightarrow Low μ_r
- ▶ Limited to 10 – 100 W



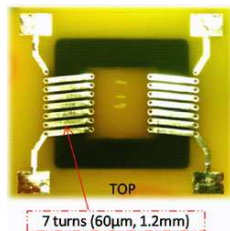
Source: Waffenschmidt et al. [9]

Planar magnetic components

- ▶ Very common, but not really embedded
- ▶ High performance
- ▶ Compatible with low (W) or high power (kW)

Embedded core

- ▶ Strong industrial development (Murata, AT&S, Würth)
- ▶ Currently limited to low power (W)



Source: Ali et al. [10]

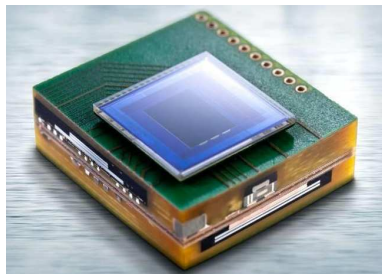
Embedding of Inserted Components

Soldered components:

- ▶ Suits most Surface-Mount Devices
- ▶ Connexions with regular vias

Vias to components:

- ▶ Requires components with Cu finish
- ▶ More compact (vias on components)



Source: Ostmann [3]

Embedding of Inserted Components

Soldered components:

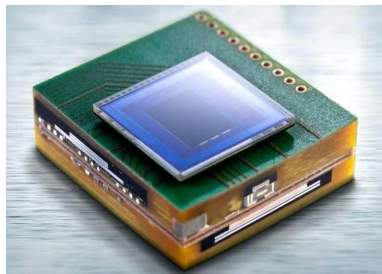
- ▶ Suits most Surface-Mount Devices
- ▶ Connexions with regular vias

Vias to components:

- ▶ Requires components with Cu finish
- ▶ More compact (vias on components)

For power electronics

- ▶ Embedding of “large” capacitors (1 μ F range)
- ▶ Embedding of gate driver ICs and peripheral components, control



Source: Ostmann [3]

Thermal Management of Embedded Components – 1

- ▶ Poor thermal conductivity of FR4 compared to ceramics ($1\text{--}7\text{ W m}^{-1}\text{ K}^{-1}$ vs $150\text{ W m}^{-1}\text{ K}^{-1}$ for AlN)
- ▶ In theory better breakdown field ($\approx 50\text{ kV mm}^{-1}$ vs. 20 kV mm^{-1})

Thermal Management of Embedded Components – 1

- ▶ Poor thermal conductivity of FR4 compared to ceramics ($1\text{--}7\text{ W m}^{-1}\text{ K}^{-1}$ vs $150\text{ W m}^{-1}\text{ K}^{-1}$ for AlN)
- ▶ In theory better breakdown field ($\approx 50\text{ kV mm}^{-1}$ vs. 20 kV mm^{-1})

To improve through-plane heat conduction:

- ▶ Micro-vias (electrically conductive), Filled cores (e.g. alumina)

Thermal Management of Embedded Components – 1

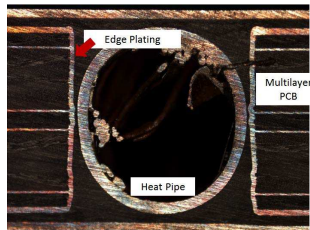
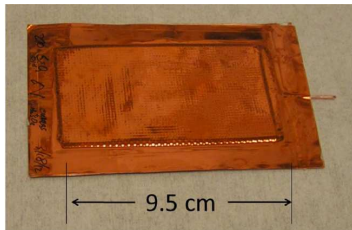
- ▶ Poor thermal conductivity of FR4 compared to ceramics ($1\text{--}7\text{ W m}^{-1}\text{ K}^{-1}$ vs $150\text{ W m}^{-1}\text{ K}^{-1}$ for AlN)
- ▶ In theory better breakdown field ($\approx 50\text{ kV mm}^{-1}$ vs. 20 kV mm^{-1})

To improve through-plane heat conduction:

- ▶ Micro-vias (electrically conductive), Filled cores (e.g. alumina)

To increase in-plane heat conduction:

- ▶ Thicker copper, Anisotropic layers (Graphite), Dual-phase

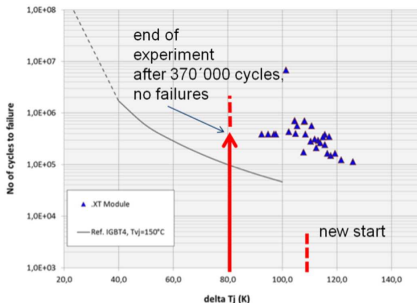


Source: left: Liew et al. [11]; right: Silvano et al. [12]

Reliability of PCB with Embedded Components

- ▶ Temperature-related issues
 - ▶ Rapid degradation above 190 °C
 - ▶ Hydrocarbon, polyimide-based PCBs resistant up to 250 °C
- ▶ Thermal cycling issues
 - ▶ CTE of PCBs much higher than ceramic or semiconductor
 - ▶ Availability of low-CTE materials
 - lacks data on large components
- ▶ Other PCB-specific issues
 - ▶ moisture absorption
 - ▶ conductive anodic filaments
- No showstopper identified yet!

Reliability of PCB with Embedded Components



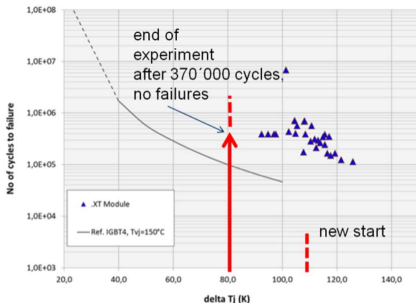
Source: Randall et al. [13]. Superimposition of reliability data for dies in PCB on Infineon's results for standard power modules



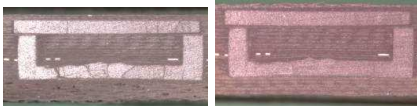
Source: Perrin et al. [14]. Left: standard FR4, right: low-CTE. Magnetic core embedded, after 1000 thermal cycles ($-50/200^\circ\text{C}$)

- ▶ Temperature-related issues
 - ▶ Rapid degradation above 190°C
 - ▶ Hydrocarbon, polyimide-based PCBs resistant up to 250°C
- ▶ Thermal cycling issues
 - ▶ CTE of PCBs much higher than ceramic or semiconductor
 - ▶ Availability of low-CTE materials
 - ➔ lacks data on large components
- ▶ Other PCB-specific issues
 - ▶ moisture sorption
 - ▶ conductive anodic filaments
- ➔ No showstopper identified yet!

Reliability of PCB with Embedded Components



Source: Randall et al. [13]. Superimposition of reliability data for dies in PCB on Infineon's results for standard power modules

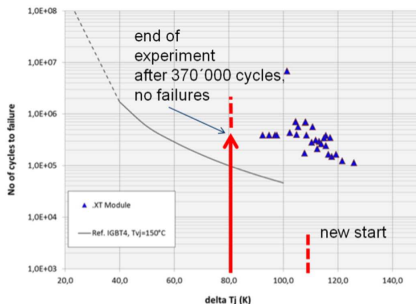


Source: Perrin et al. [14]. Left: standard FR4, right: low-CTE. Magnetic core embedded, after 1000 thermal cycles (-50/200 °C)

- ▶ Temperature-related issues
 - ▶ Rapid degradation above 190 °C
 - ▶ Hydrocarbon, polyimide-based PCBs resistant up to 250 °C
- ▶ Thermal cycling issues
 - ▶ CTE of PCBs much higher than ceramic or semiconductor
 - ▶ Availability of low-CTE materials
 - lacks data on large components
- ▶ Other PCB-specific issues
 - ▶ moisture absorption,
 - ▶ conductive anodic filaments. . .

→ No showstopper identified yet!

Reliability of PCB with Embedded Components



Source: Randall et al. [13]. Superimposition of reliability data for dies in PCB on Infineon's results for standard power modules



Source: Perrin et al. [14]. Left: standard FR4, right: low-CTE. Magnetic core embedded, after 1000 thermal cycles (-50/200 °C)

- ▶ Temperature-related issues
 - ▶ Rapid degradation above 190 °C
 - ▶ Hydrocarbon, polyimide-based PCBs resistant up to 250 °C
 - ▶ Thermal cycling issues
 - ▶ CTE of PCBs much higher than ceramic or semiconductor
 - ▶ Availability of low-CTE materials
 - lacks data on large components
 - ▶ Other PCB-specific issues
 - ▶ moisture absorption,
 - ▶ conductive anodic filaments. . .
- No showstopper identified yet!

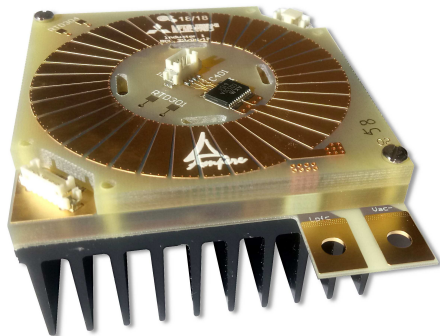
Conclusions on Embedding Technology

Application to Power Electronics

- ▶ Many components can be embedded
 - ▶ Dies require Cu finish
 - ▶ Large components?
- ▶ Acceptable thermal performance

Open questions

- ▶ Find the sweet spot:
 - ▶ Embedding power dies only?
 - ▶ Embed everything?
 - ▶ Or somewhere in-between?
- ▶ Are flat converters desirable?
- ▶ How to design for embedding?



SiC PFC Cell, 750 W, PCB size $7 \times 7 \times 1 \text{ cm}^3$. SiC dies, gate driver circuit, PFC inductor and temperature sensors embedded in PCB.

Introduction

State of the Art of PCB embedding

Proposition – Design Tools for Power Electronics

Conclusions

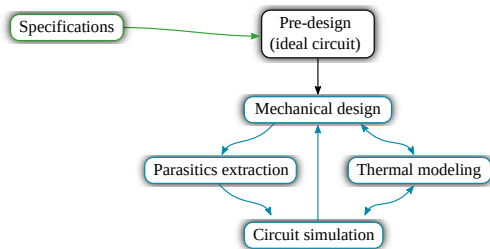
Design in Power Electronics – Current State

Specifications

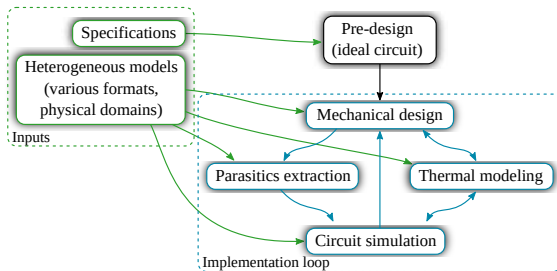
Design in Power Electronics – Current State



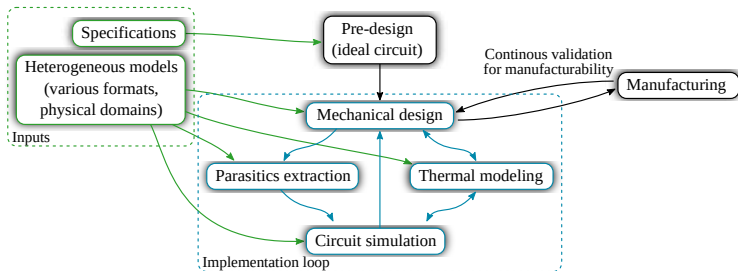
Design in Power Electronics – Current State



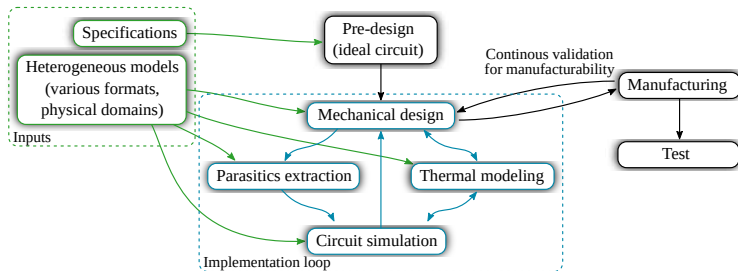
Design in Power Electronics – Current State



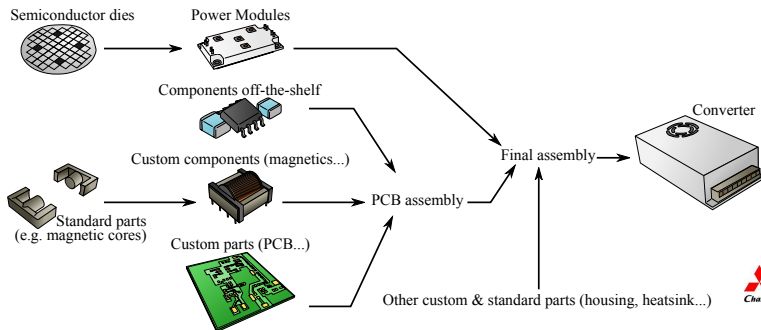
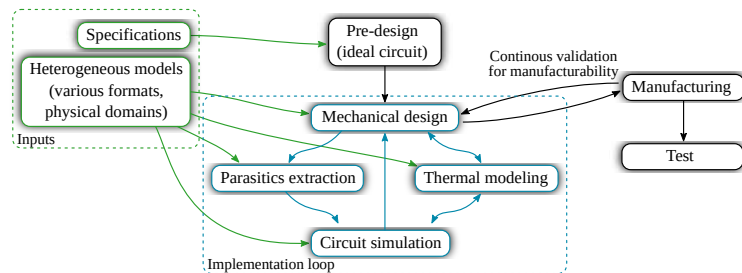
Design in Power Electronics – Current State



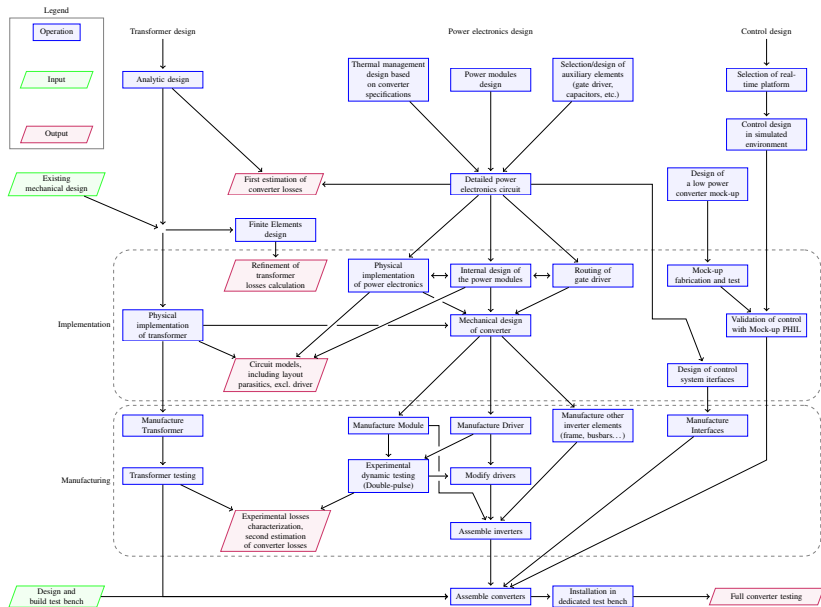
Design in Power Electronics – Current State



Design in Power Electronics – Current State

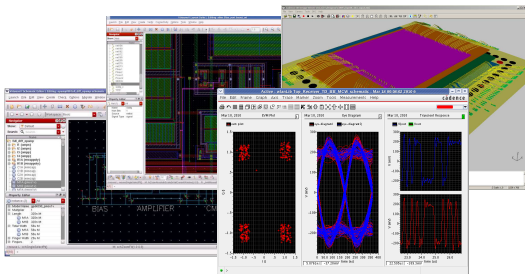


Design in Power Electronics – Real-case example



Source: Supergrid Institute, submitted article

Design in Microelectronics

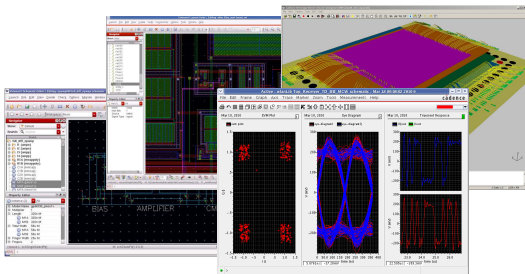


Source: Cadence

Integrated software for

- ▶ Circuit design
- ▶ Routing
- ▶ Simulation
- ▶ Mask generation. . .

Design in Microelectronics



Source: Cadence

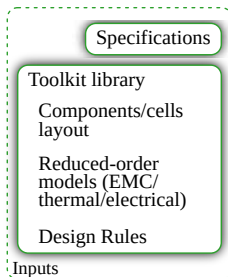
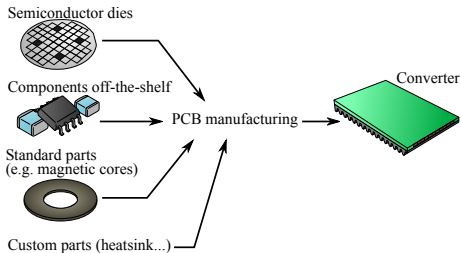
Integrated software for

- ▶ Circuit design
- ▶ Routing
- ▶ Simulation
- ▶ Mask generation. . .

Why is it not available in power electronics?

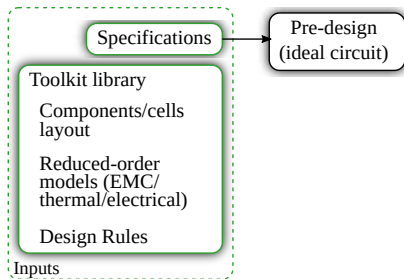
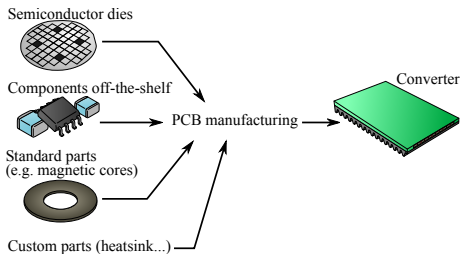
- ▶ powerful financial incentive for virtual prototyping
 - ▶ A 45 nm mask set costs ≈ 2 M\$ (source: Electronic design, 2009)
- ▶ Limited technology variations
 - ▶ Most of the circuit is monolithic
 - ▶ No flexibility allowed in technology configuration
- Manufacturers supply a “design toolkit” describing the technology

Proposition – Design in Power Electronics



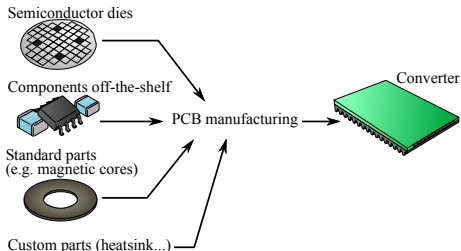
- ▶ Rationalized manufacturing
- ➔ Reduce design variability
- ▶ Design Toolkit for simulation and validation
- ➔ Design for manufacturing

Proposition – Design in Power Electronics

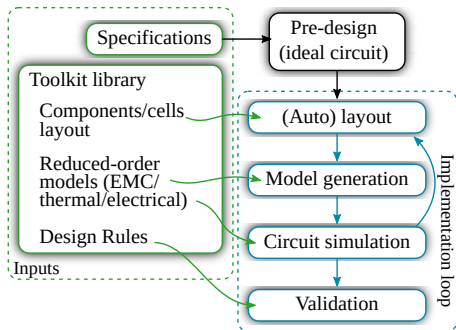


- ▶ Rationalized manufacturing
- ➔ Reduce design variability
- ▶ Design Toolkit for simulation and validation
- ➔ Design for manufacturing

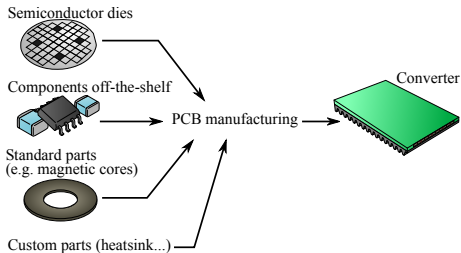
Proposition – Design in Power Electronics



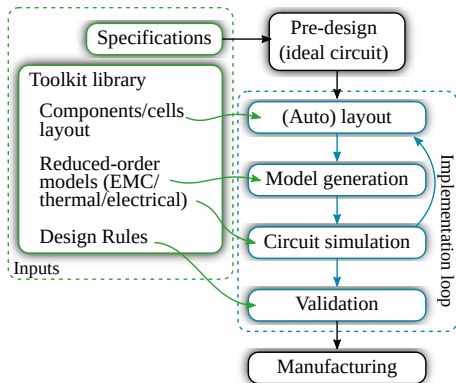
- Rationalized manufacturing
- ➔ Reduce design variability
- Design Toolkit for simulation and validation
- ➔ Design for manufacturing



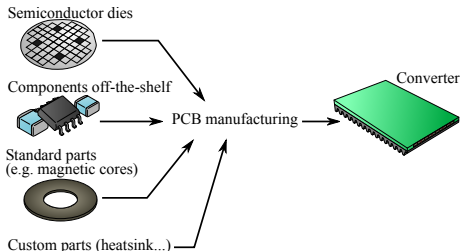
Proposition – Design in Power Electronics



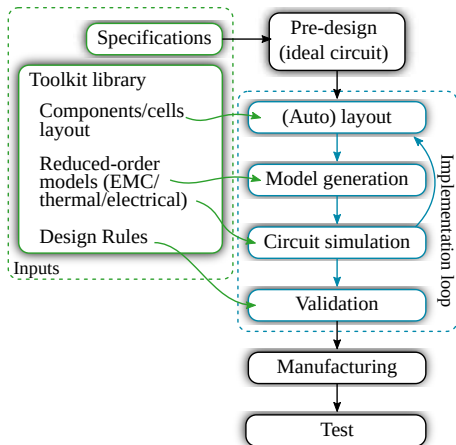
- Rationalized manufacturing
- Reduce design variability
- Design Toolkit for simulation and validation
- Design for manufacturing



Proposition – Design in Power Electronics



- Rationalized manufacturing
- ➔ Reduce design variability
- Design Toolkit for simulation and validation
- ➔ Design for manufacturing



Proposition – Expected Outcomes

What would we get?

- ▶ **Fully custom** designs, as opposed to modular
- ▶ Automatic **Design for Manufacturing** (*fabless* approach)
- ▶ Single, well controlled technology:
 - Qualification: of technology rather than products
 - Scalability: same technology for test and production runs
 - Prototyping: share panels across projects
- Basically all the usual features in IC design.
- ▶ Reduced choice of components
 - ▶ Must be in the toolkit library
- ▶ Reduced design flexibility
 - ▶ The lower degrees of freedom, the simpler the toolkit

Proposition – Expected Outcomes

What would we get?

- ▶ **Fully custom** designs, as opposed to modular
- ▶ Automatic **Design for Manufacturing** (*fabless* approach)
- ▶ Single, well controlled technology:
 - Qualification: of technology rather than products
 - Scalability: same technology for test and production runs
 - Prototyping: share panels across projects
- Basically all the usual features in IC design.
- ▶ Reduced choice of components
 - ▶ Must be in the toolset library
- ▶ Reduced design flexibility
 - ▶ The lower degrees of freedom, the simpler the toolset

Proposition – Expected Outcomes

What would we get?

- ▶ **Fully custom** designs, as opposed to modular
- ▶ Automatic **Design for Manufacturing** (*fabless* approach)
- ▶ Single, well controlled technology:
 - Qualification:** of technology rather than products
 - Scalability:** same technology for test and production runs
 - Prototyping:** share panels across projects

→ Basically all the usual features in IC design.

- ▶ Reduced choice of components
 - Must be in the toolset library
- ▶ Reduced design flexibility
 - The lower degrees of freedom, the simpler the toolset

Proposition – Expected Outcomes

What would we get?

- ▶ **Fully custom** designs, as opposed to modular
- ▶ Automatic **Design for Manufacturing** (*fabless* approach)
- ▶ Single, well controlled technology:
 - Qualification:** of technology rather than products
 - Scalability:** same technology for test and production runs
 - Prototyping:** share panels across projects
- ➔ Basically all the usual features in IC design.

- ▶ Reduced choice of components
 - ➔ Must be in the toolset library
- ▶ Reduced design flexibility
 - ➔ The lower degree of freedom, the simpler the toolset

Proposition – Expected Outcomes

What would we get?

- ▶ **Fully custom** designs, as opposed to modular
- ▶ Automatic **Design for Manufacturing** (*fabless* approach)
- ▶ Single, well controlled technology:
 - Qualification:** of technology rather than products
 - Scalability:** same technology for test and production runs
 - Prototyping:** share panels across projects
- Basically all the usual features in IC design.

At what cost?

- ▶ Reduced choice of components
 - ▶ Must be in the toolset library
- ▶ Reduced design flexibility
 - ▶ The lower degree of freedom, the simpler the toolset

Proposition – Expected Outcomes

What would we get?

- ▶ **Fully custom** designs, as opposed to modular
- ▶ Automatic **Design for Manufacturing** (*fabless* approach)
- ▶ Single, well controlled technology:
 - Qualification:** of technology rather than products
 - Scalability:** same technology for test and production runs
 - Prototyping:** share panels across projects
- Basically all the usual features in IC design.

At what cost?

- ▶ Reduced choice of components
 - ▶ Must be in the toolkit library
- ▶ Reduced design flexibility

Fig. The lower degree of freedom, the simpler the toolset

Proposition – Expected Outcomes

What would we get?

- ▶ **Fully custom** designs, as opposed to modular
 - ▶ Automatic **Design for Manufacturing** (*fabless* approach)
 - ▶ Single, well controlled technology:
 - Qualification:** of technology rather than products
 - Scalability:** same technology for test and production runs
 - Prototyping:** share panels across projects
- Basically all the usual features in IC design.

At what cost?

- ▶ Reduced choice of components
 - ▶ Must be in the toolkit library
- ▶ Reduced design flexibility
 - ▶ The fewer degrees of freedom, the simpler the toolkit

Proposition – Getting There

► **Better design tools**

- Large choice of existing software (PCB layout, circuit simulators, EM modeling)
- Need to identify suitable modelling approach (speed/accuracy trade-off)
- Software “glue” required for automatic model generation

► **Define design rules for PCB embedding**

- Required for automatic design validation
- Long experimental work required

► **The impact on the supply chain must also be assessed**

Proposition – Getting There

- ▶ **Better design tools**

- ▶ Large choice of existing software (PCB layout, circuit simulators, EM modeling)
- ▶ Need to identify suitable modelling approach (speed/accuracy trade-off)
- ▶ Software “glue” required for automatic model generation

- ▶ **Define design rules for PCB embedding**

- ▶ Required for automatic design validation
- ▶ Long experimental work required.

- ▶ The impact on the supply chain must also be assessed

Proposition – Getting There

- ▶ **Better design tools**
 - ▶ Large choice of existing software (PCB layout, circuit simulators, EM modeling)
 - ▶ Need to identify suitable modelling approach (speed/accuracy trade-off)
 - ▶ Software “glue” required for automatic model generation
- ▶ **Define design rules for PCB embedding**
 - ▶ Required for automatic design validation
 - ▶ Long experimental work required.
- ▶ **The impact on the supply chain must also be assessed**

Introduction

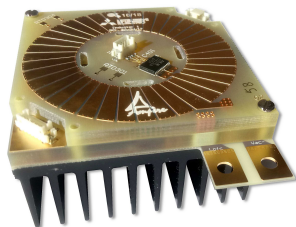
State of the Art of PCB embedding

Proposition – Design Tools for Power Electronics

Conclusions

Conclusions – Exploiting the PCB Embedding

- ▶ PCB embedding is very promising
 - ▶ Provides a single, unified technology for power electronics (W to 10's of kW range)
 - ▶ High performance
 - ▶ Scalable, reasonable cost. . .
- ▶ Situation comparable to microelec. in the 70's
 - ▶ Many technologies available, but no standard
 - ▶ No separation between design and manuf.
 - Need for Design Rules and uniformization
- ▶ Large effort required on the design tools
 - ▶ Allow *Design for Manufacturing*
 - ▶ Objective: efficient virtual prototyping



Bibliography I



J. W. Kolar, F. Krismer, and H.-P. Nee, "What are the big challenges in power electronics?," in *Proceedings of CIPS*, (Nürnberg), 2014.



L. Kerachev, A. Andreta, Y. Lembeye, and J.-C. Crébier, "Generic approach for design, configuration and control of modular converters," in *International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management*, (Nuremberg), pp. 212 – 219, VDE Verlag, May 2017.



A. Ostmann, "Evolution and future of embedding technology," in *IMAPS/NMI workshop "disappearing die – embed your chips"*, 2016.



E. Hoene, "Ultra Low Inductance Package for SiC," in *ECPE workshop on power boards*, ECPE, 2012.



Y. PASCAL, D. Labrousse, M. Petit, S. LEFEBVRE, and F. Costa, "PCB-Embedding of Power Dies Using Pressed Metal Foam," in *Power Conversion and Intelligent Motion (PCIM) Europe*, (Nuremberg, Germany), June 2018.



A. B. Sharma, D. Paul, M. Kreck, Y. Rahmoun, P. Anders, M. Gruber, and T. Huesgen, "PCB embedded power package with reinforced top-side chip contacts," in *2016 6th Electronic System-Integration Technology Conference (ESTC)*, pp. 1–5, Sept 2016.

Bibliography II



Dupont., “Dupont interra embedded passives materials – interra HK04 planar capacitor laminate,” tech. rep., Dupont, 2007.



J. Andresakis, “Embedded Capacitors,” presentation, Oak-Mitsui Technologies, Nov. 2005.



E. Waffenschmidt, B. Ackermann, and J. A. Ferreira, “Design Method and Material Technologies for Passives in Printed Circuit Board Embedded Circuits,” *IEEE Transactions on Power Electronics*, vol. 20, pp. 576–584, May 2005.



M. Ali, E. Labouré, F. Costa, and B. Revol, “Design of a hybrid integrated EMC filter for a DC–DC power converter,” *IEEE Transactions on Power Electronics*, vol. 27, no. 11, pp. 4380–4390, 2012.



L.-A. Liew, C.-Y. Lin, R. Lewis, S. Song, Q. Li, R. Yang, and Y. Lee, “Flexible thermal ground planes fabricated with printed circuit board technology,” *Journal of Electronic Packaging*, vol. 139, no. 1, pp. 011003–011003–10, 2017.



J. S. de Sousa, P. Fulmek, M. Unger, P. Haumer, J. Nicolics, M. A. Ras, and D. May, “Enhanced in-plane heat transport in embedded mini heat pipes PCB,” *International Symposium on Microelectronics*, vol. 2017, no. 1, pp. 000130–000134, 2017.

Bibliography III



R. Randoll, W. Wondrak, and A. Schletz, "Lifetime and manufacturability of integrated power electronics," *Microelectronics Reliability*, vol. 64, pp. 513 – 518, 2016.

Proceedings of the 27th European Symposium on Reliability of Electron Devices, Failure Physics and Analysis.



R. Perrin, B. Allard, C. Buttay, N. Quentin, W. Zhang, R. Burgos, D. Boroyevich, P. Preciat, and D. Martineau, "2 MHz high-density integrated power supply for gate driver in high-temperature applications," in *Applied Power Electronics Conference and Exposition (APEC)*, (Long Beach, United States), Mar. 2016.

Thank you for your attention

cyril.buttay@insa-lyon.fr

This work was funded by Mitsubishi Electric Research Centre Europe and the French Agency for Technology and Research (ANRT). The authors thank Mr. Jean-Christophe CRÉBIER and Yves LEMBEYE, from G2ELab for their fruitful discussions.