Multiphysics Modeling of SiC-Based Power Inverters in (H)EVS: Integrated Cooling

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Acknowledgements

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We would like to acknowledge the help and support of
Dr. Michael Guyenot and Dr. Martin Rittner.

1. Background

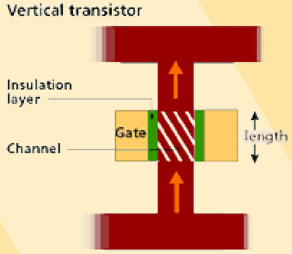
1.1 Advantages and Challenges of Silicon Carbide (SiC)

Although SiC devices offer superior performance over conventional Si devices, these advantages are **limited by packaging technologies**.

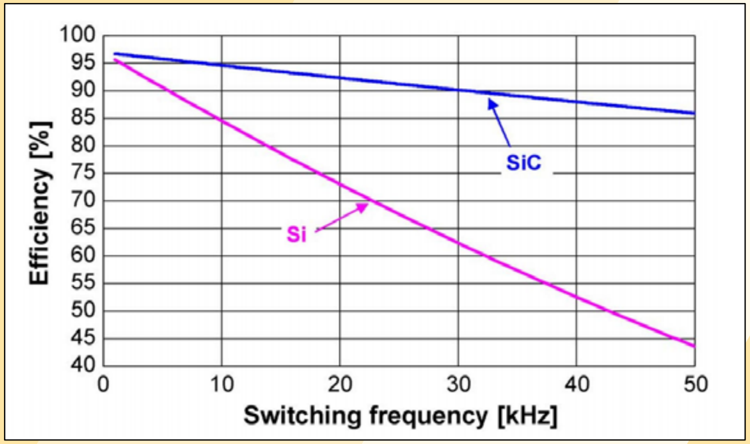
Figures of Merit for Semiconductors

in Vertical Conduction Devices

	Si	GaAs	6H-SiC	4H-SiC	GaN
JFM	1.0	1.8	277.8	215.1	215.1
BFM	1.0	14.8	125.3	223.1	186.7
FSFM	1.0	11.4	30.5	61.2	65.0
BSFM	1.0	1.6	13.1	12.9	52.5
FPFM	1.0	3.6	48.3	56.0	30.4
FTFM	1.0	40.7	1470.5	3424.8	1973.6



There are many advantages to SiC – higher breakdown voltage, higher current ratings, higher operating temperature, higher switching speed, and lower switching losses.



Efficiency of Power Converters

With its improved performance and efficiency, SiC allows for increased power density, highly desirable in transport applications.

However, this miniaturization aggravates thermal management challenges as its smaller form factor contributes to more highly concentrated and localized heat flux densities.

C. Chen, F. Luo, and Y. Kang, "A review of SiC power module packaging: Layout, material system and integration," *CPSS Transactions on Power Electronics and Applications*, vol. 2, no. 3, pp. 170-186, 2017.

1. Background

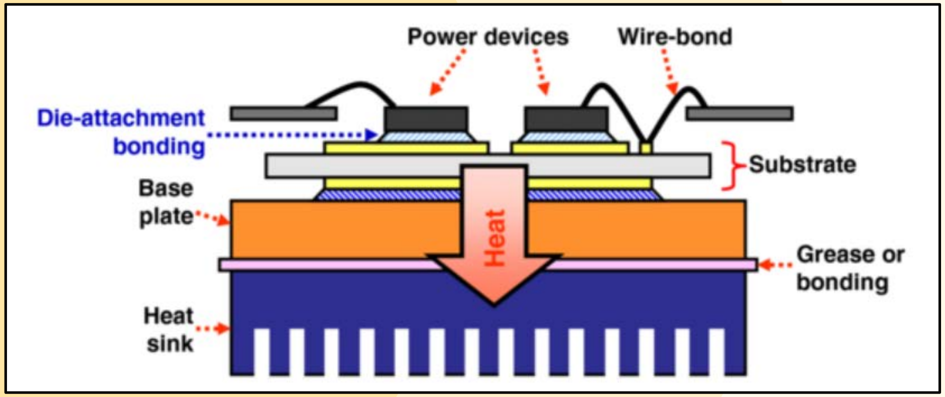
1.2 Evolution of Packaging Technologies

Some of the key limitations of current packaging technologies include:

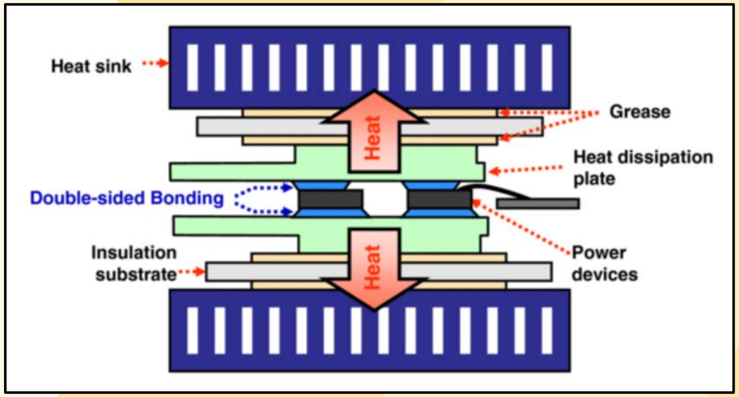
- Electrical Parasitics
- Heat Spreading and Cooling
- Thermal Resistance from Pathways
- Incompatibility with High-Temperature Operation (< 200°C)

Evolution of Packaging Technologies

Standard Packaging



Advanced Packaging



- **Wire Bonds**
  - Lengthy interconnections
  - Larger footprint
- **Single-Sided Cooling**
  - Higher thermal resistances

- **Stacked Structure**
  - Minimization of parasitics
  - Reduction of package layers
- **Double-Sided Cooling**
  - Lower thermal resistance
- **Modularity**
  - Versatility of integration

S. W. Yoon, M. D. Glover, H. A. Mantooth, and K. Shiozaki, "Reliable and repeatable bonding technology for high temperature automotive power modules for electrified vehicles," *Journal of Micromechanics and Microengineering*, vol. 23, no. 1, pp. 15-17, 2012.

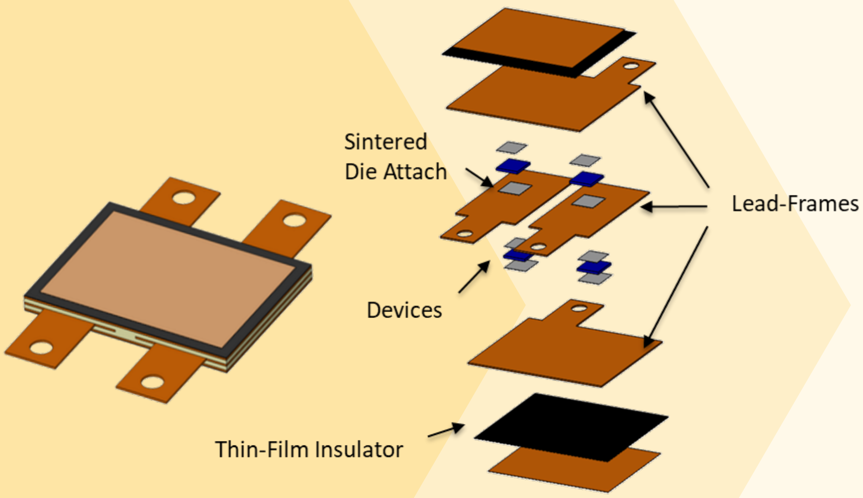
1. Background

1.3 Beyond the Current State-of-the-Art: Packaging for Transition to SiC

Some examples of new unique approaches include a **true 3D integration with vertical stacking of power devices**.

3D Stacked Rectifier Module

Haksun Lee

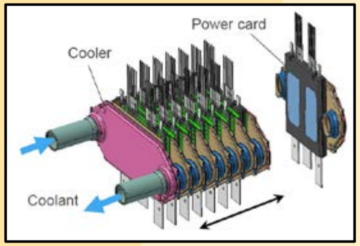


Advantages

- Minimization of electrical parasitics
- Improved thermal performance in steady-state and transient conditions
- Ease of scalability in power
- Compatibility with current and future manufacturing processes

Integrated Cooling for Power Inverters

Ryan Wong



O. Kitazawa, T. Kikuchi, M. Nakashima, Y. Tomita, H. Kosugi, and T. Kaneko, "Development of Power Control Unit for Compact-Class Vehicle," ed: SAE International, 2016.

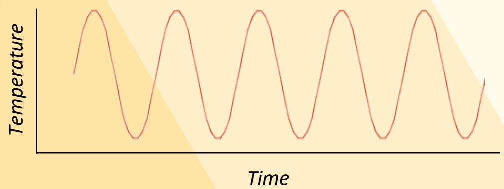
- More functional integration for heat spreading and cooling
- Combination of stacked modular design with integrated cooling
- Miniaturization

2. Strategic Need

2.1 Importance of Thermal Management

Thermal Cycling

Ambient

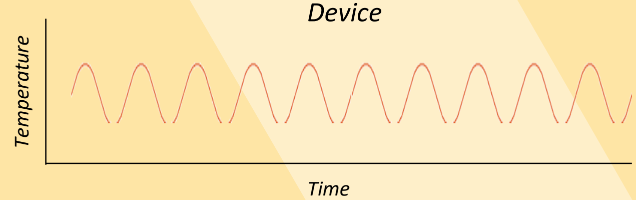


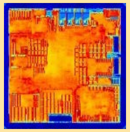
Need for Integrated Cooling

Different Cycling Types

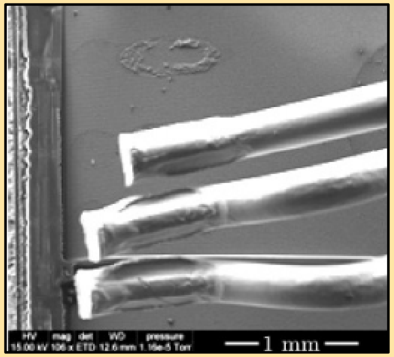
Power Cycling

Device

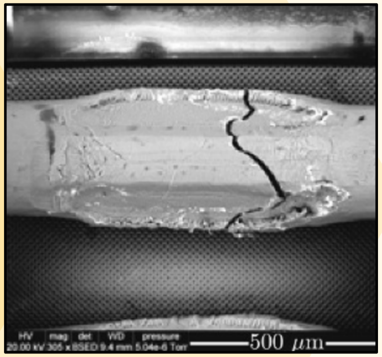




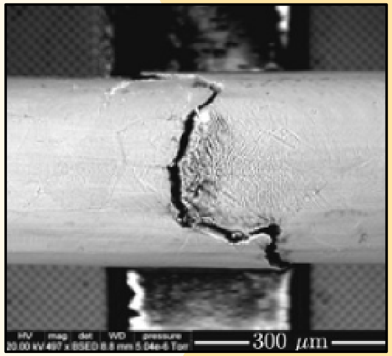
Thermal Failures in Power Electronics



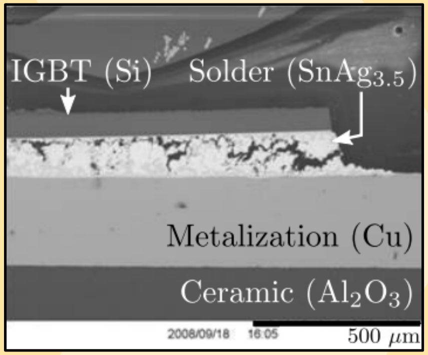
Bond Wire Liftoff



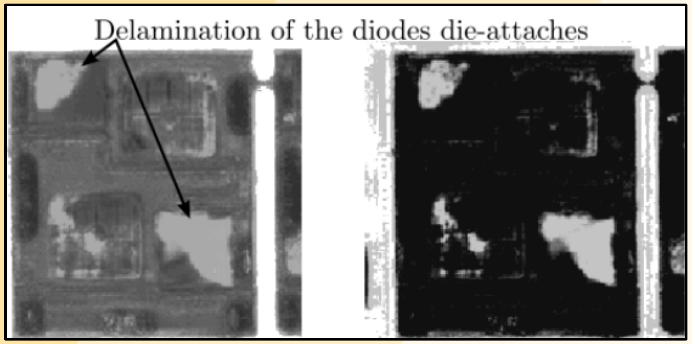
Heel Cracking



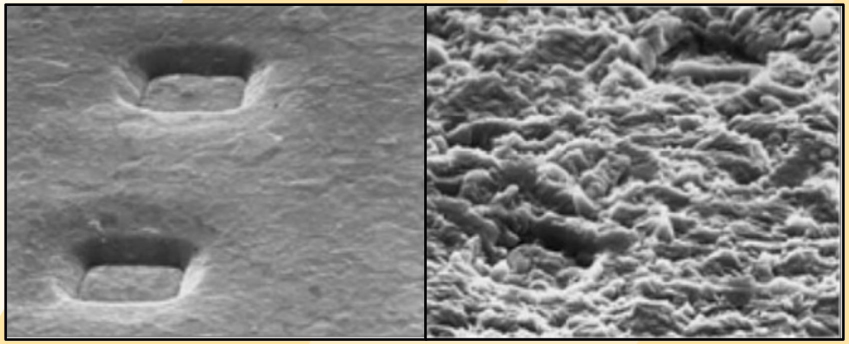
Loop Cracking



Solder Joint Cracking



Delamination



Metallization Reconstruction

3. Objectives

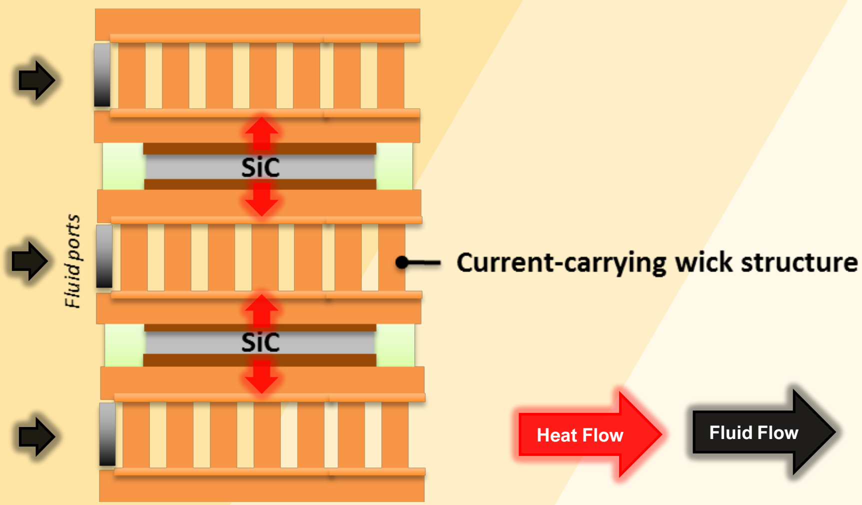
Model, design, and demonstrate **integrated** single-phase **cooling solutions** for **SiC 3D lead frame based power cards**:

- Advanced **cold plates as high current terminals**
- Direct chip cooling using **liquid dielectrics and 3D bridge structures**

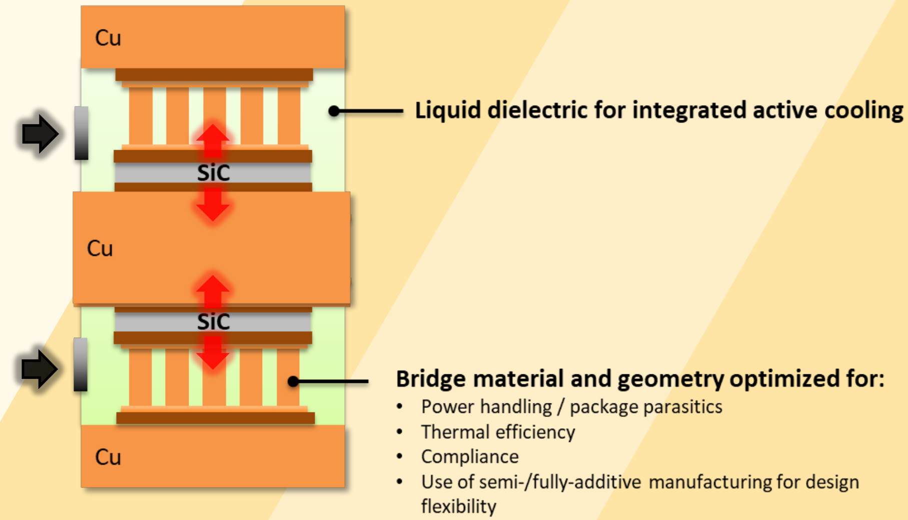
Benefits of integrated cooling

- Direct cooling
- Elimination of insulating layers
- Reduction of thermal resistance
- Miniaturization

Advanced Cold Plates as Current Terminals

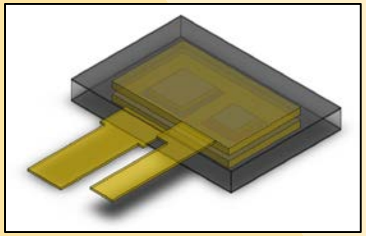


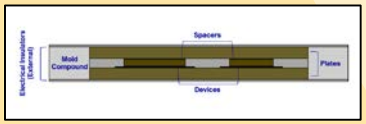
Direct Chip Cooling with Liquid Dielectric

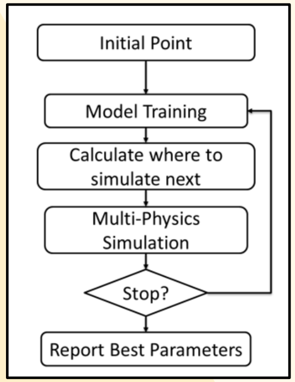


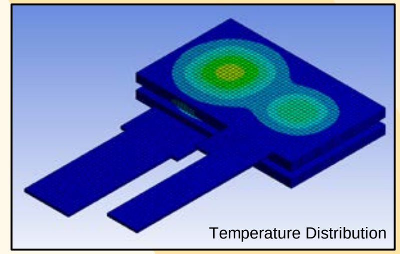
4. Technical Approach

4.1 Exploration of Integrated Cooling Solutions – Methodology

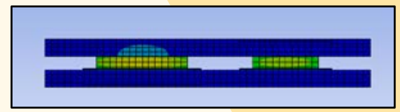


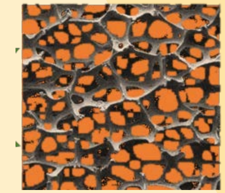




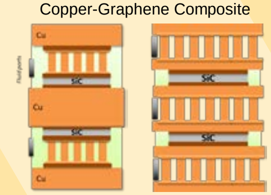


Temperature Distribution





Copper-Graphene Composite



Create a parametric model, and define important design considerations.

Apply machine learning algorithms for optimization of model, and to determine the design.

Develop materials to achieve the design and their optimized parameters.

Parametric Geometry and Multiphysics Environment

- Creation of a fully parametric geometry to account for any possible parameters that can affect performance – layout, geometry, materials.

Interface with Machine Learning

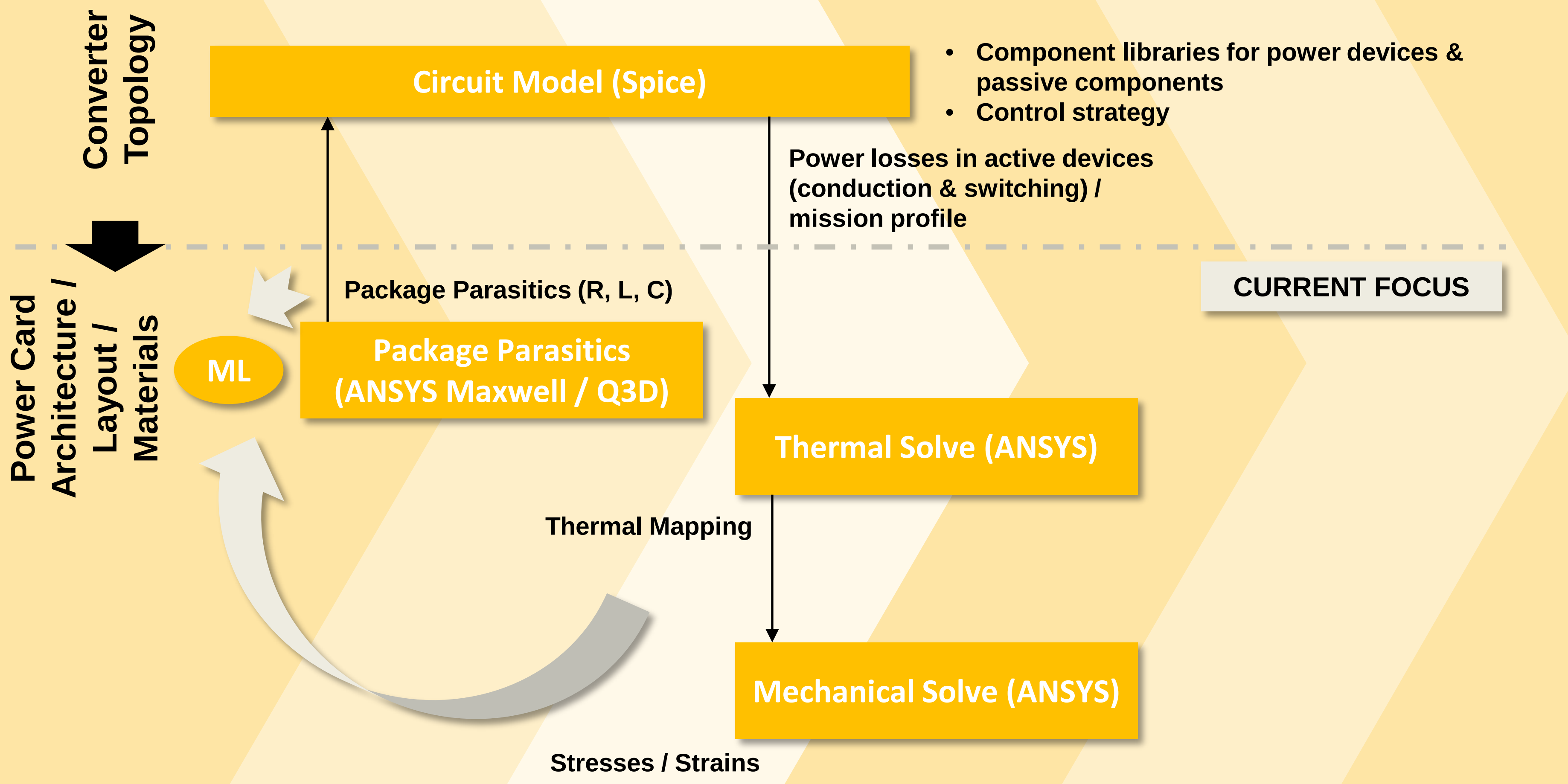
- Optimization of wick structures in the auto-generation and combination of different layout, geometries, and materials for optimal performance.

Material Development

- Synthesis and characterization of potential material candidates such as graphene composites.

4. Technical Approach

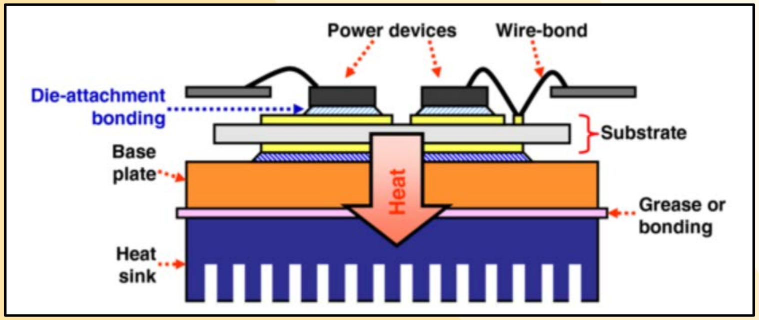
4.2 Hierarchy and Coupling of Models



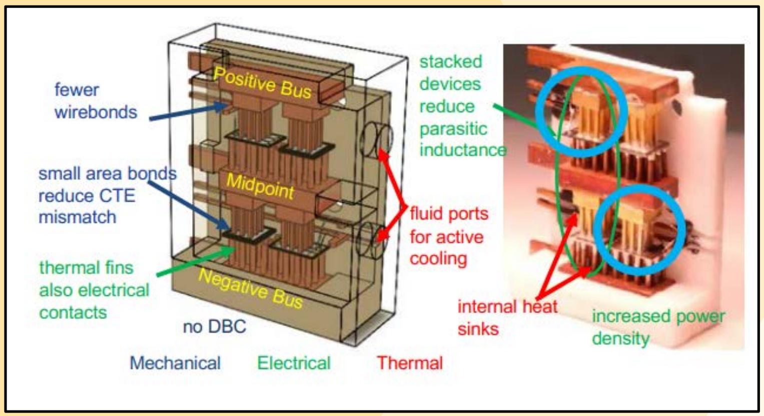
5. Comparison with Prior Art

5.1 Examples of Stacked Power Modules

Standard Power Module



Stacked Power Module

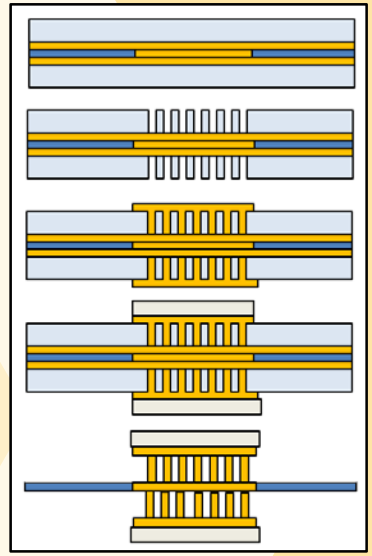


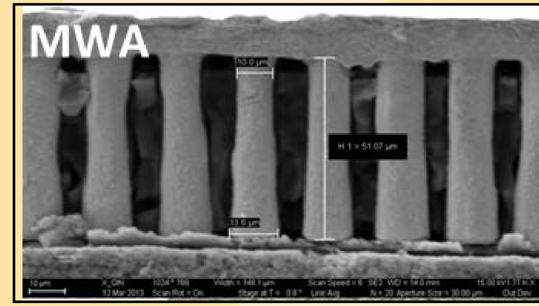
Limitations of Prior Art

- *Current state of additive manufacturing.*
- *Low temperature processing results in lesser material properties.*
- *Trade-offs between material and structural factors.*
- *Poor reliability.*

Microwire Arrays as Interconnections

Xian Jin





Advancement Beyond Prior Art

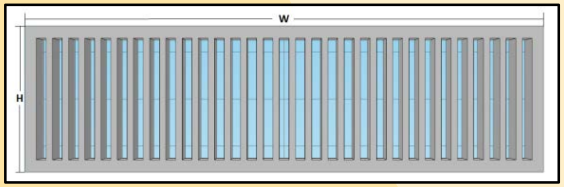
- *Similar structures have been designed and demonstrated with these microwire arrays as interconnections.*
- *Possible to combine the advantages of both additive and semi-additive manufacturing – to achieve ideal structures and material properties.*
- *Integration of machine learning algorithms to optimize structure and material combinations.*

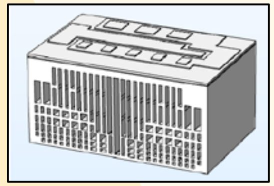
L. M. Boteler, V. A. Niemann, D. P. Urciuoli, and S. M. Miner, "Stacked power module with integrated thermal management," in *2017 IEEE International Workshop On Integrated Power Packaging (IWIPP)*, 5-7 April 2017, pp. 1-5.

5. Comparison with Prior Art

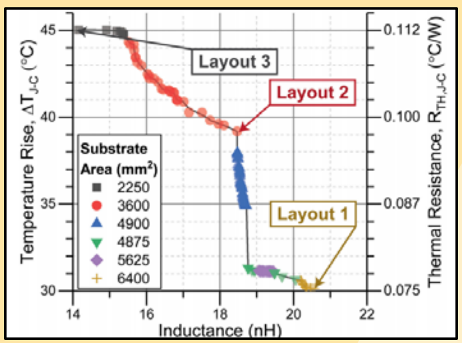
5.2 Examples of Optimization of Power Electronics

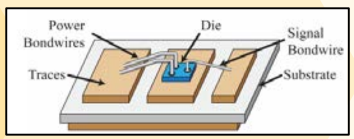
Generation of Patterns for Heat Sinks

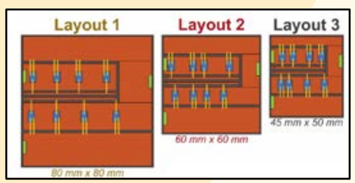




Optimization of Layout for Power Modules





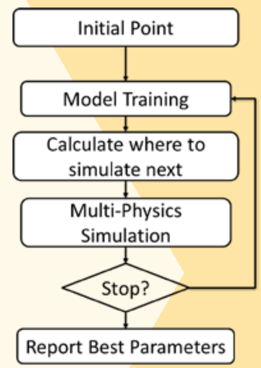


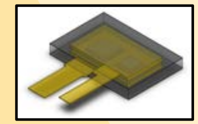
Limitations of Prior Art

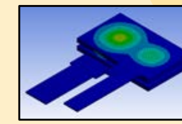
- *Narrow scope in terms of design considerations.*
- *Only select parts of cooling systems have been analyzed – such as heat sinks or layout of heat-generating devices.*
- *It is necessary that prior art must evolve beyond for design and optimization of next-generation power electronics.*

Bayesian Learning for Optimization and Analysis of Si-Based Inverter Package

Hakki M. Torun







Parameter	Material	Unit	Min	Max
Diode/Switch Spacer Thickness	Cu	mm	0.20	3.00
Collector Plate Thickness	Cu	mm	0.05	3.00
Emitter Plate Thickness	Cu	mm	0.05	3.00
Collector Insulator Thickness	Dielectric Thin Film	mm	0.25	1.00
Emitter Insulator Thickness	Dielectric Thin Film	mm	0.25	1.00
All Joint Thicknesses (5 separate params.)	Solder	mm	0.05	0.10

Advancement Beyond Prior Art

- *Multi-objective optimization, inclusive of all important design consideration.*
- *Determine optimal combination of package architecture, circuit topology, and materials to meet performance metrics.*

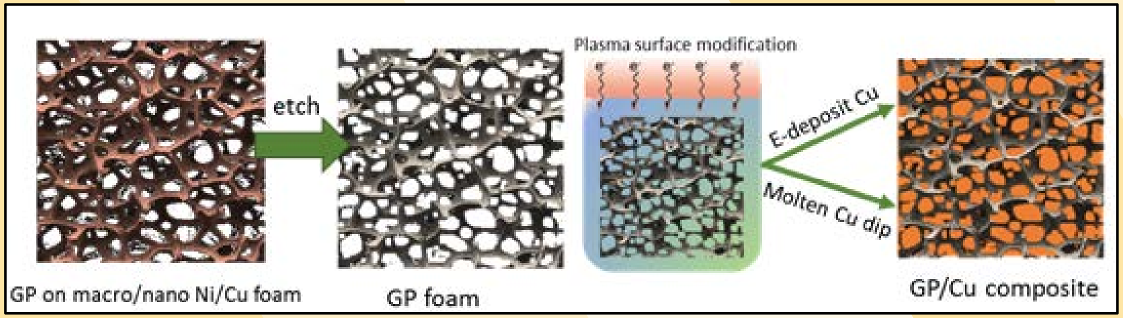
T. M. Evans *et al.*, "PowerSynth: A Power Module Layout Generation Tool," *IEEE Transactions on Power Electronics*, vol. 34, no. 6, pp. 5063-5078, 2019.
T. Wu, B. Ozpineci, M. Chinthavali, W. Zhiqiang, S. Debnath, and S. Campbell, "Design and optimization of 3D printed air-cooled heat sinks based on genetic algorithms," in *2017 IEEE Transportation Electrification Conference and Expo (ITEC)*, 22-24 June 2017 2017, pp. 650-655

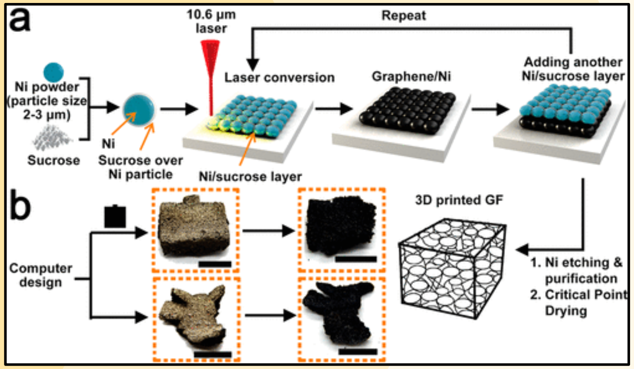
6. Latest Results

6.2 Material Development

Beyond innovations in design and structure, material development for high thermal and electrical conductivity as well as tailorable coefficient of thermal expansion.

Graphene-Foam-Based Cu-GP Composites





(a) Synthesis of graphene foams by exposure of sugar and nickel powder in a CO_2 laser followed by subsequent etching

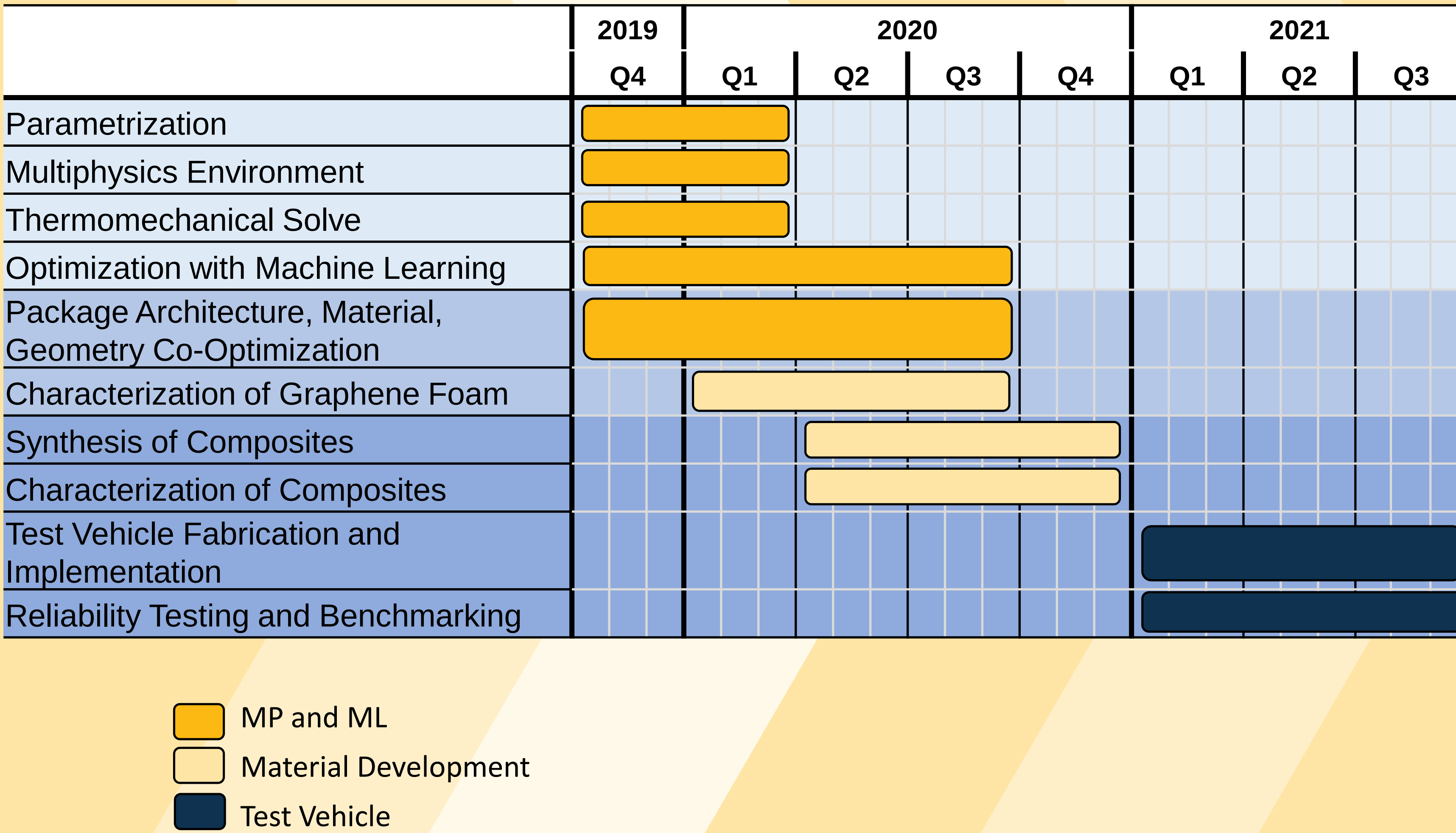
(b) Selective laser sintering process can be used to design and controllably fabricate a wide range of structures

Characterization of Graphene Foams and their Composites

- AFM, SEM/EDX, nanoindentation, BET, among other porosity measurement methods
- Thermal, electrical and mechanical properties of the composites characterized using thermo-reflectance and 3ω methods, 4-point probe, tensile/indentation tests as well as CTE measurements using Digital Image Correlation

J. Sha, Y. Li, R. Villegas Salvatierra, T. Wang, P. Dong, Y. Ji, et al., "Three-dimensional printed graphene foams," Acs Nano, vol. 11, pp. 6860-6867, 2017.

7. Timeline


2019
2020
2021
Q4
Q1
Q2
Q3
Q4
Q1
Q2
Q3
Parametrization
Multiphysics Environment
Thermomechanical Solve
Optimization with Machine Learning
Package Architecture, Material, Geometry Co-Optimization
Characterization of Graphene Foam
Synthesis of Composites
Characterization of Composites
Test Vehicle Fabrication and Implementation
Reliability Testing and Benchmarking
MP and ML
Material Development
Test Vehicle

8. Summary

Framework for Methodology

Creation of Parametric Geometry and Multiphysics Environment

- Demonstrated a fully parametric model of a power module.
- Ran initial simulations for thermal and mechanical solves.

Interface with Machine Learning

- Integrated a multiphysics environment to an optimization algorithm for the design and optimization structures to meet performance metrics.

Plan for Material Development

- Established a plan for synthesis and characterization of copper-graphene composites with eventual implementation into test vehicles.