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Thermal Packaging Challenges for Next-Generation Power Electronics

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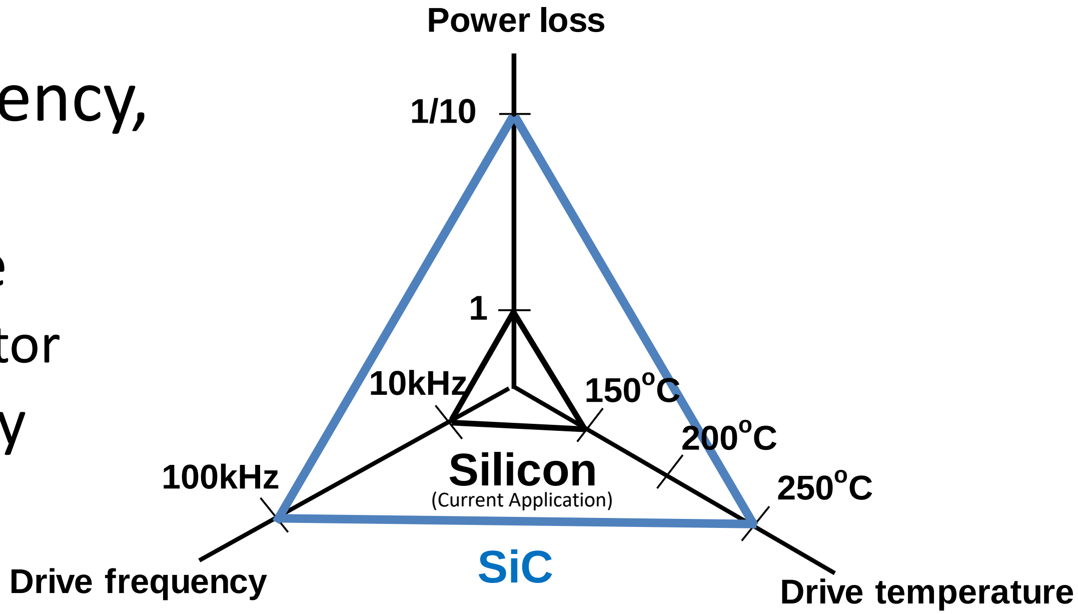
Overview

- Characteristics of Wide Band-Gap Devices
- Requirements of Next-Generation Packaging
- Packaging Trends for Power Electronics
- Relevant Future Technologies
  - Near-Junction Cooling
  - Thermal Ground Planes
  - Transient Liquid Phase Bonding
  - Self-Healing Die Attach
- Conclusions

Characteristics of Wide Band-Gap Devices

- Increased device breakdown electric field
- High temperature operation
- High switching frequency, low switching loss
  - Reduced passive size
    - E.g. inductor, capacitor
  - Higher power density



* Ref.: Ogawa, et al., 2016

Requirements of Next-Generation Packaging

- Packaging strategies that support higher maximum junction temperature: 150 °C → 250 °C
  - E.g. new material systems must be developed for bonding, substrate, encapsulation
- Thermal management techniques that enable higher power density (orders-of-magnitude)
  - E.g. new approaches needed beyond conventional remote cooling techniques
- Careful consideration of package for low parasitic inductance and electromagnetic interference (EMI)

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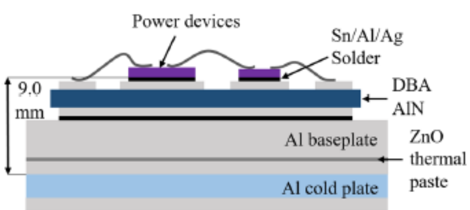
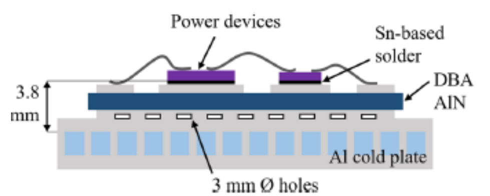
Packaging Trends for Power Electronics

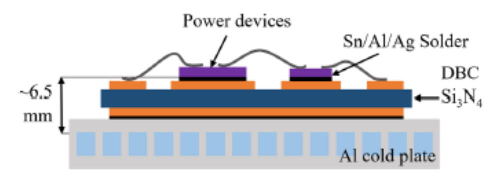
- Historical approaches in automotive:



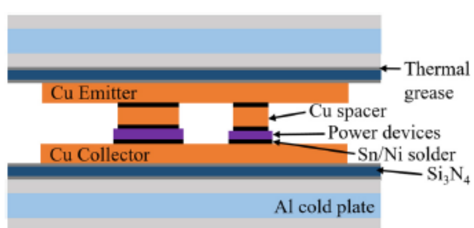
Toyota Prius 2004



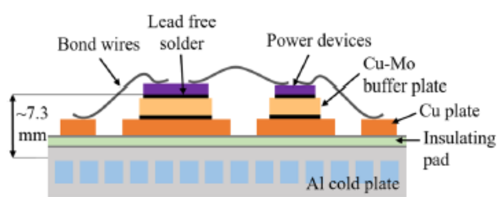
Toyota Prius 2010



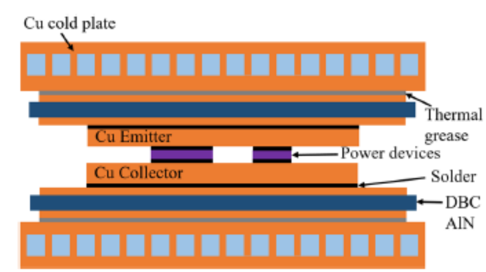
Honda Accord 2014



Lexus LS 600h 2008



Nissan Leaf 2012



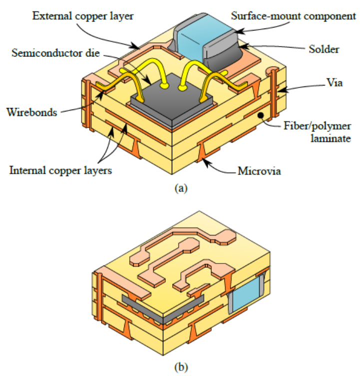
Chevrolet Volt 2016

* Ref.: Broughton, et al., 2018

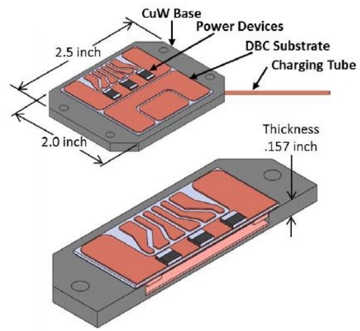
Multiple layers and single-phase remote cooling dominate applications, but limit packaging breakthrough

Packaging Trends for Power Electronics

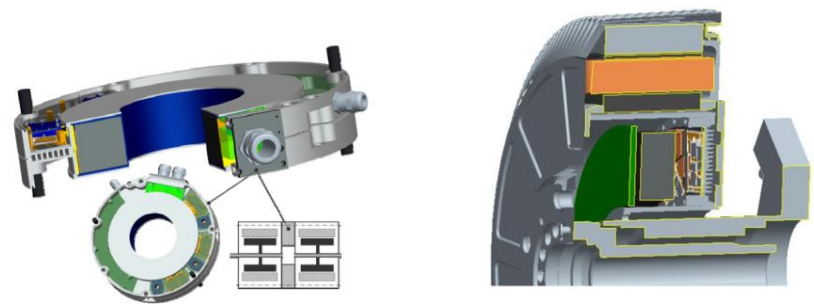
- Efforts towards higher levels of integration:



* Ref.: Buttay, et al., 2018

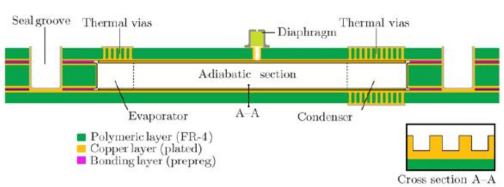


* Ref.: Hose, et al., 2017



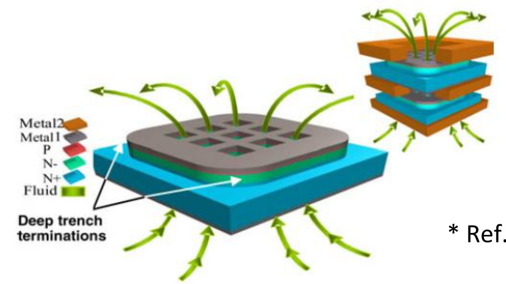
* Ref.: Marz, et al., 2010

New Form Factors & Motor Integration



* Ref.: Wits, et al., 2010

Substrate (e.g. PCB, DBC) Embedding



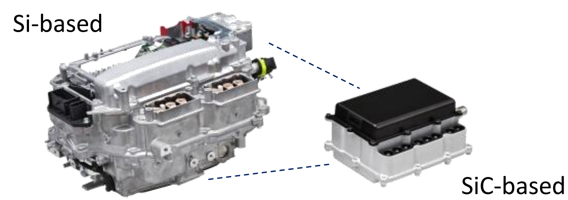
* Ref.: Vladimirova, et al., 2013

Device Embedded Cooling

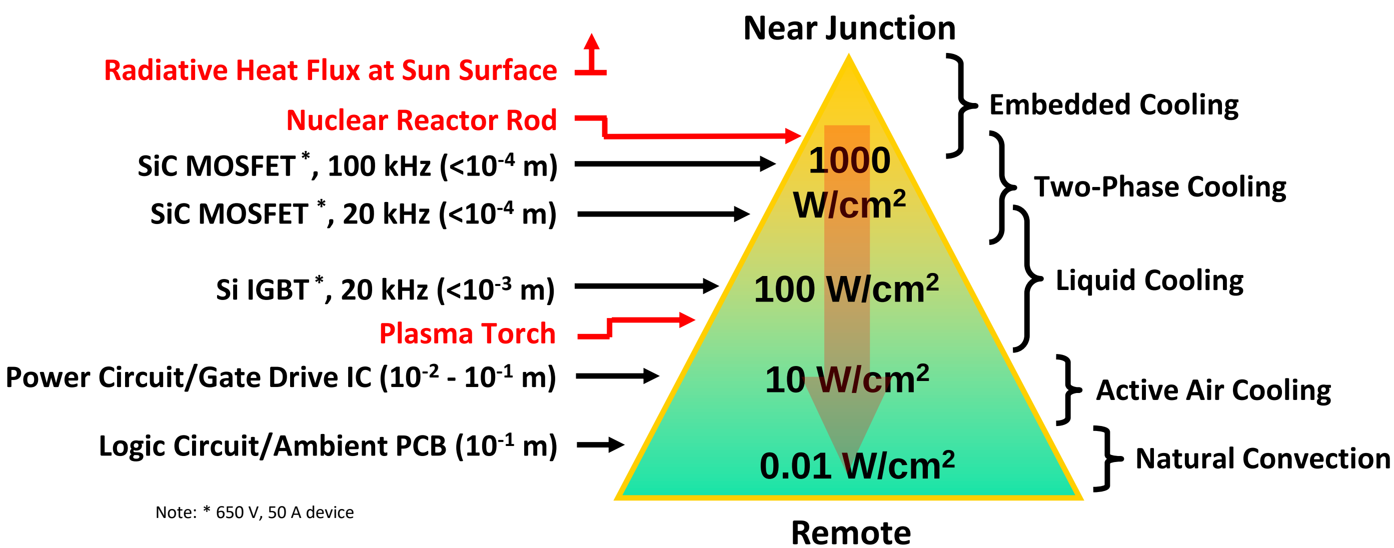
High power density → embedding + integration → novel packaging and different process workflows

Packaging Trends for Power Electronics

- Future transition to wide band-gap (WBG) devices; e.g., SiC or GaN
  - Device breakdown voltage ↑
  - Temperature tolerance ↑
  - Switching speed ↑, passive size ↓, power control unit (PCU) size ↓



- Trend in device heat flux and cooling technology



Power density drives (conductive path) packaging approach and (convective path) cooling technology

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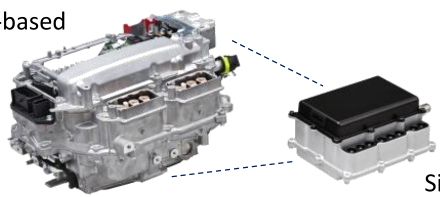
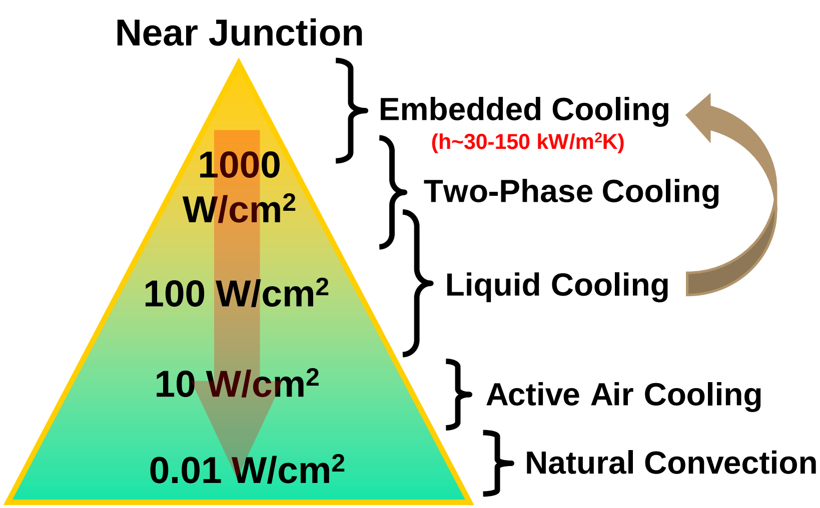
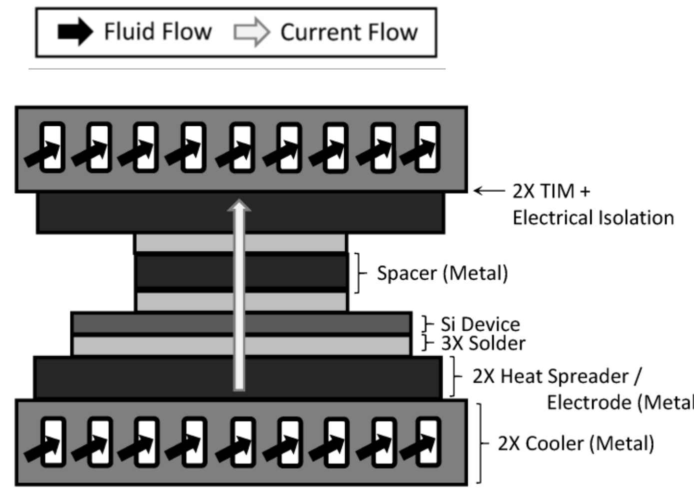
Near-Junction Cooling – Motivation

- Order-of-magnitude downsizing requires new packaging concepts
  - Package conductive thermal resistance → driving factor



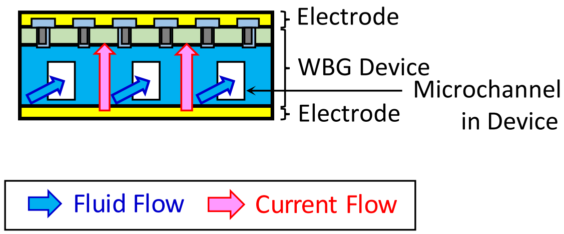




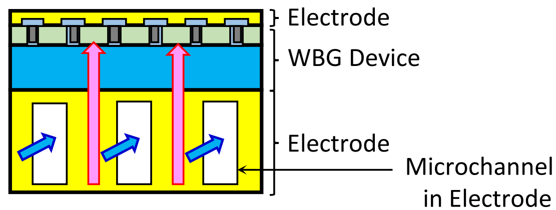
Conventional Power Card Structure

Near-Junction Cooling – Concepts

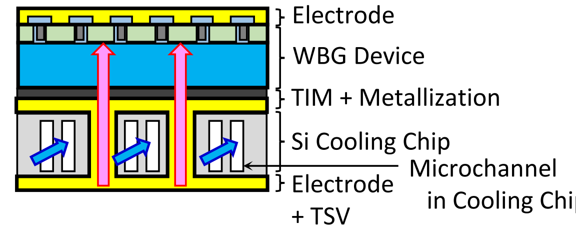
- Three concepts for vertical current WBG devices



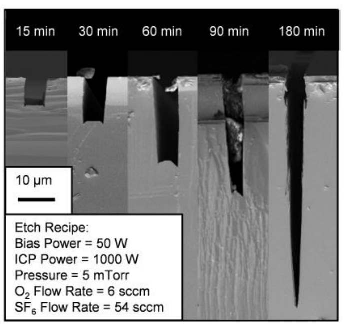
Concept A
(μChannels Fabricated in Device)



Concept B
(μChannels Fabricated in Electrode)

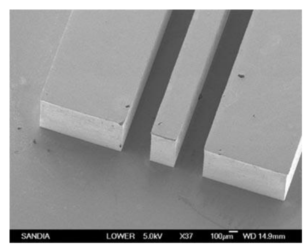


Concept C
(μChannels Fabricated in Cooling Chip)



SiC Etching SoA

Ref.: Dowling, et al., 2017.
DOI: 10.1109/JMEMS.2016.2621131



LIGA Microfabrication
(lithography, electroplating and molding)

Ref.: Michael.Forman - Own work, CC BY 3.0, https://commons.wikimedia.org/w/index.php?curid=7155729

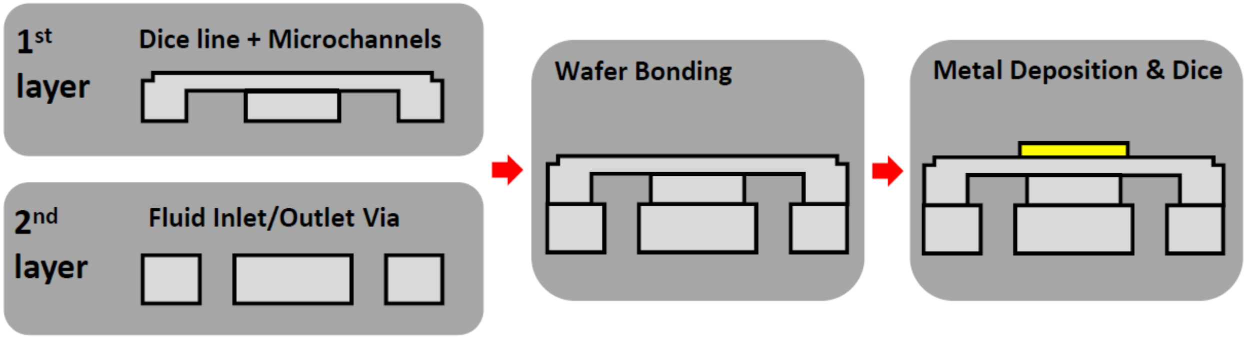
Qualitative Comparison of Concepts

	Concept A	Concept B	Concept C
Thermal Performance	○	○	△
Electrical performance	△	○	○
Fabrication feasibility	△	×	○

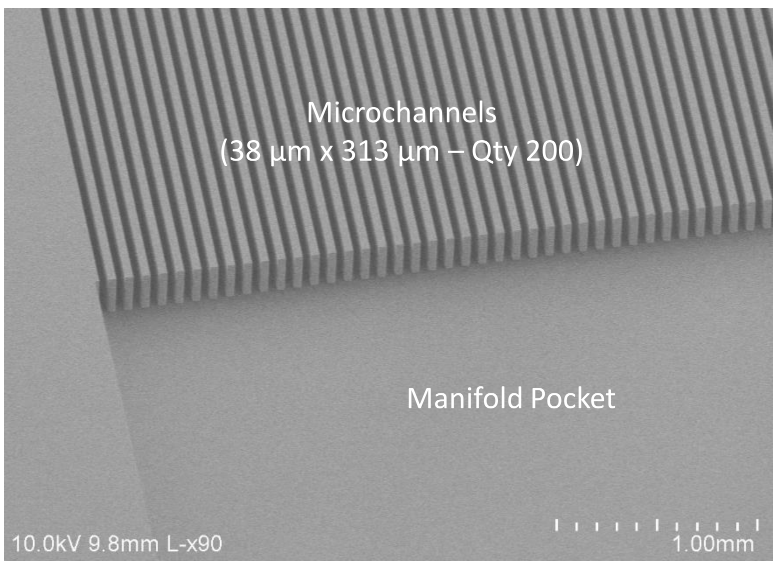
Leverage established MEMS microfabrication processes in silicon to explore Concept C cooling chip

Near-Junction Cooling – 1st Prototype Fab

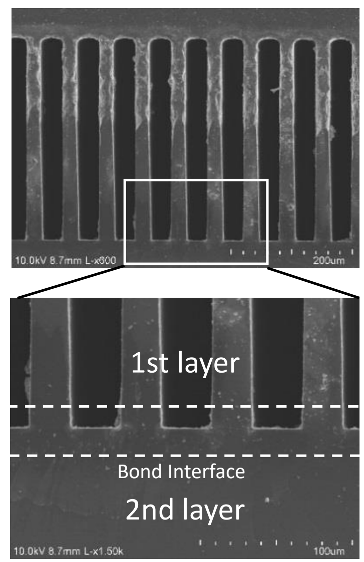
- Straight microchannel prototype fabrication using Bosch process



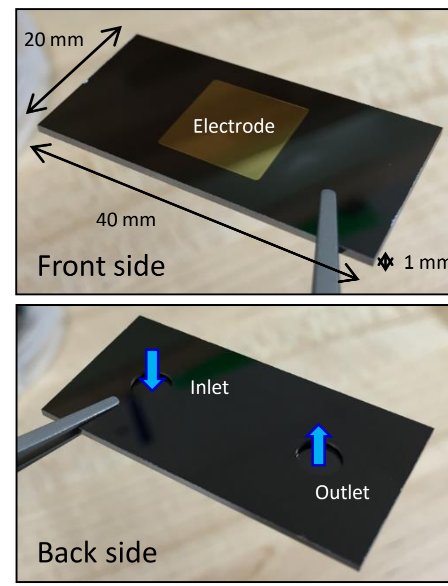
LNF User Facility



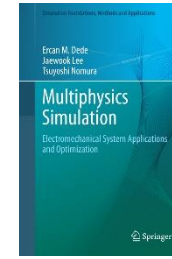
SEM Image of 1st Layer



SEM Image of Bonded Assembly Cross-Section



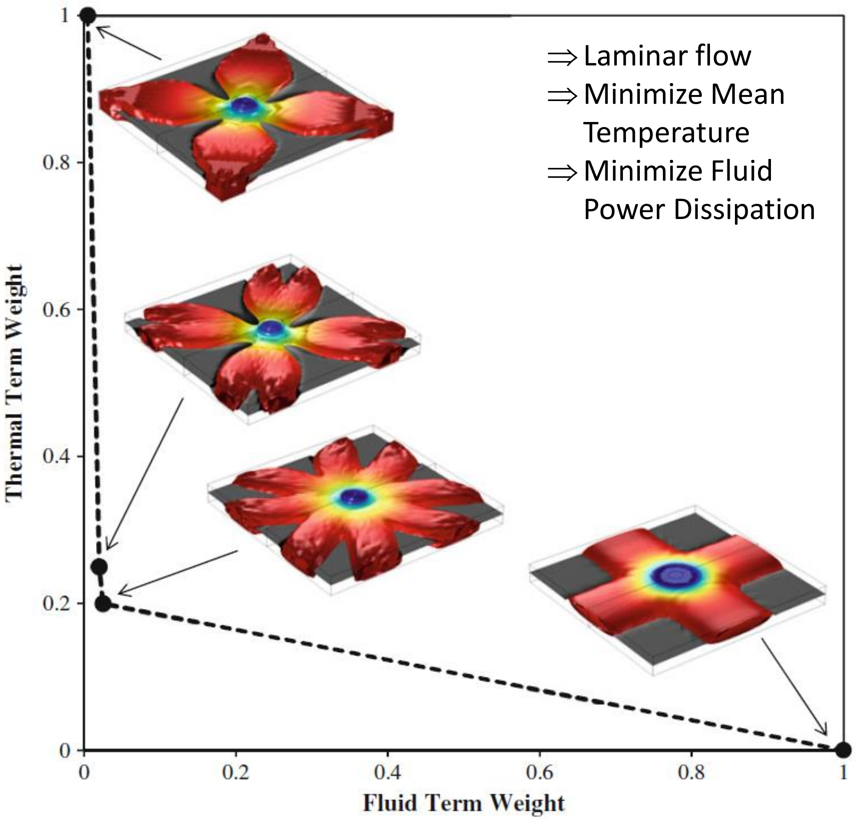
Si Cooling Chip Prototype



Near-Junction Cooling – 2nd Prototype Design

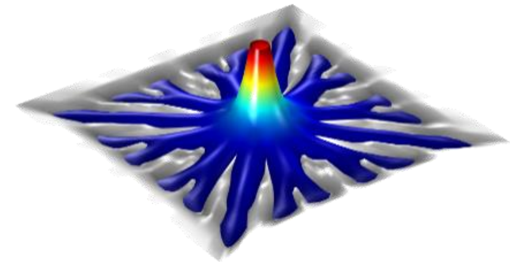
*Ref.: Dede, et al. (2014) Springer

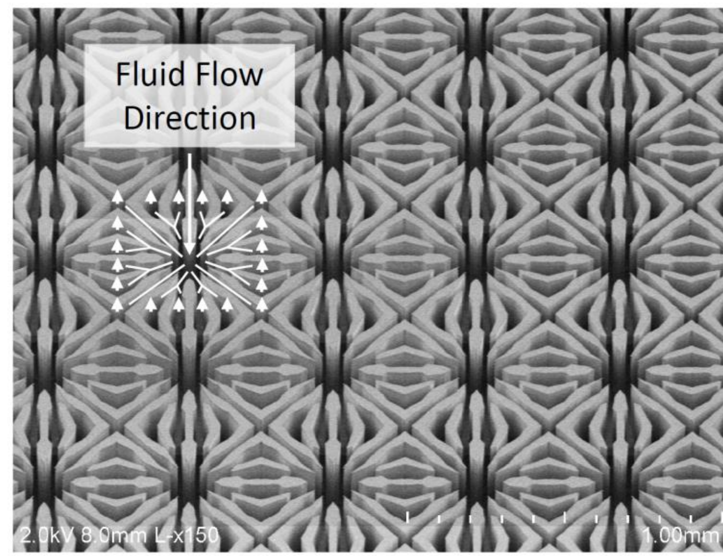
- Microchannel unit cell design optimized for conjugate heat transfer



Pareto Front of Multi-Objective Design Optimization in 3-D for Thermal-Fluid Problem

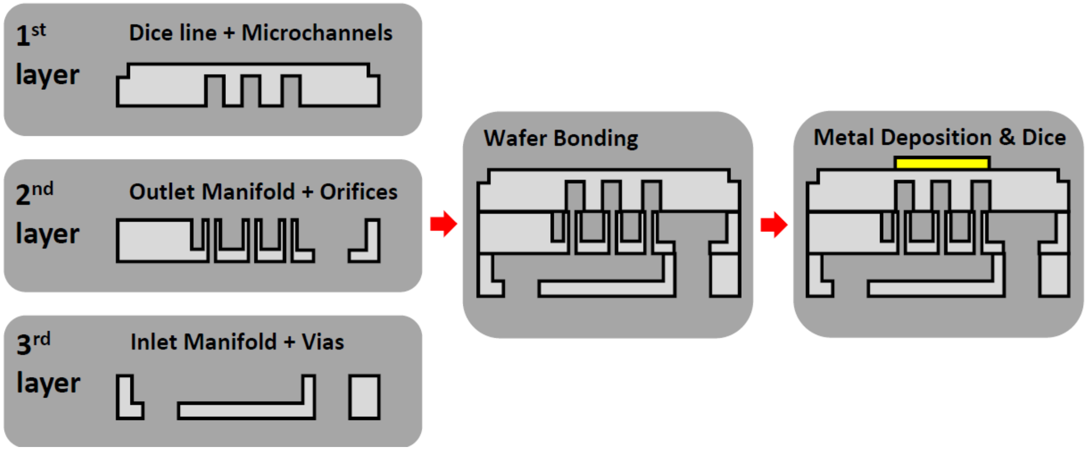
2-D Design Result

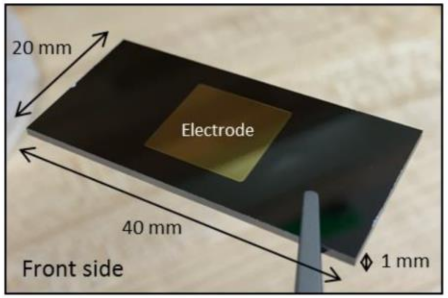




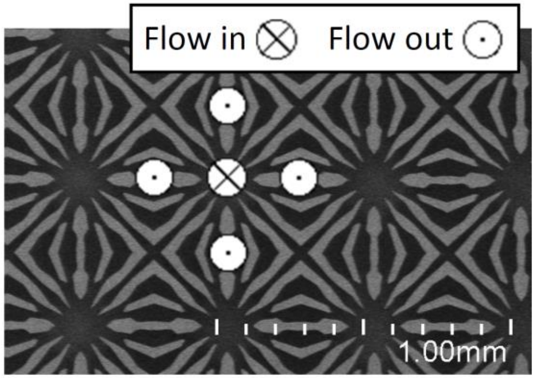
SEM Image of 1st Layer Microchannel Structure
(Zoomed Isometric View)

Near-Junction Cooling – 2nd Prototype Fab

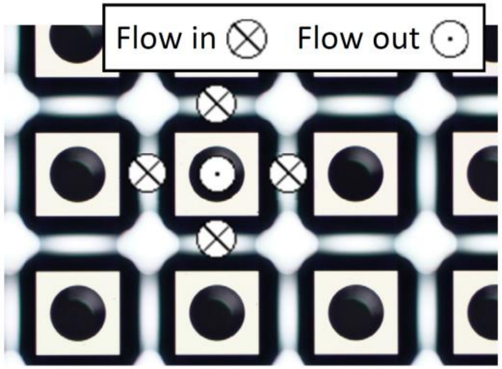




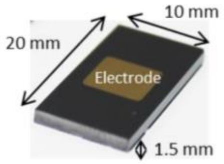
Straight Microchannel Design



1st Layer



2nd Layer



Optimized Unit Cell Design

2nd prototype cooling chip design is one-quarter footprint size of straight microchannel cooling chip

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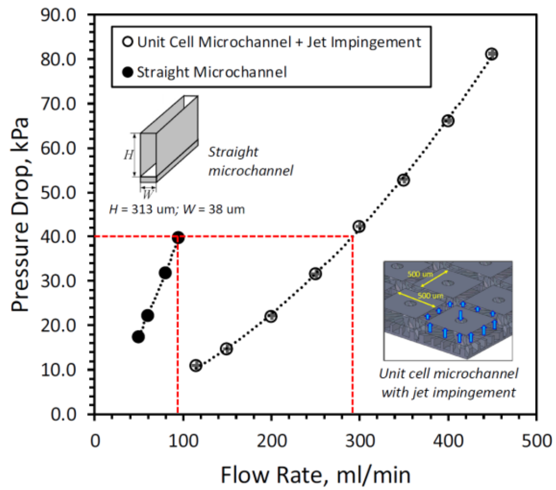
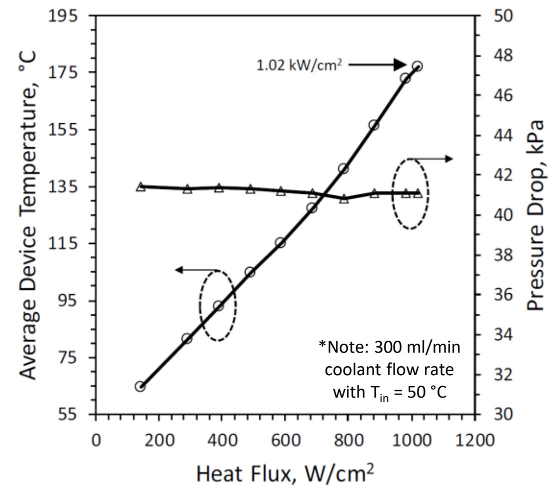
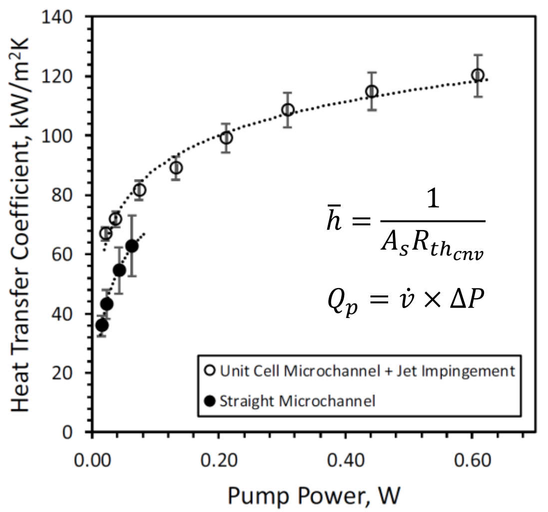
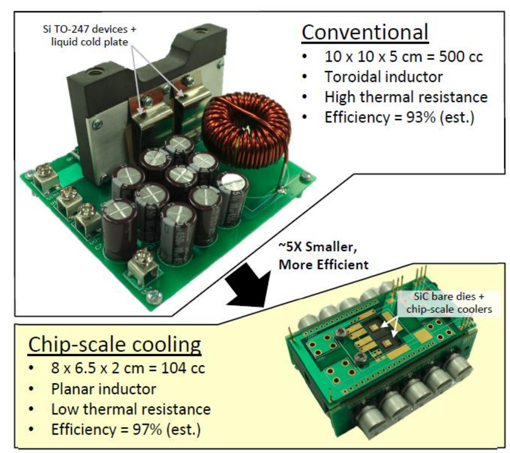
Near-Junction Cooling – Experimental Results









Toward Order-of-Magnitude Size Reduction

For same ΔP , UC microchannel design supports 3X higher flow rate → larger heat transfer coefficient

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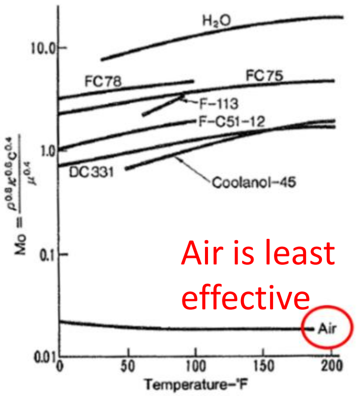
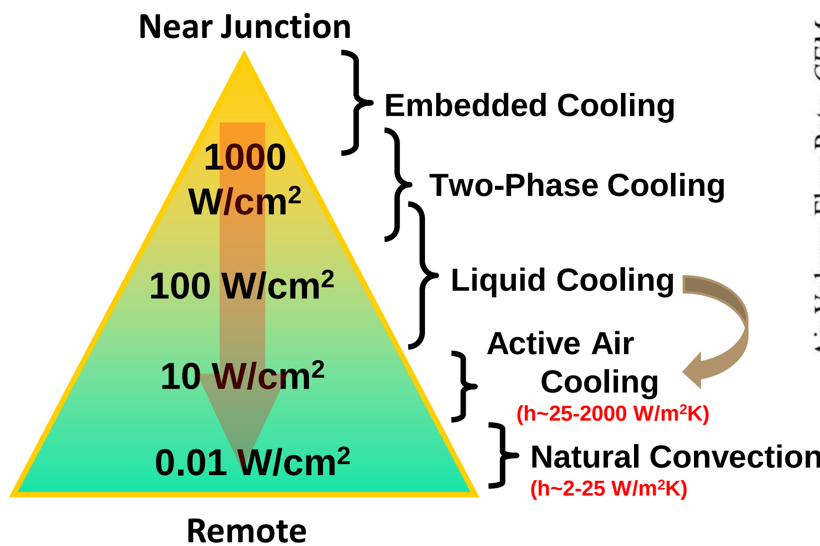
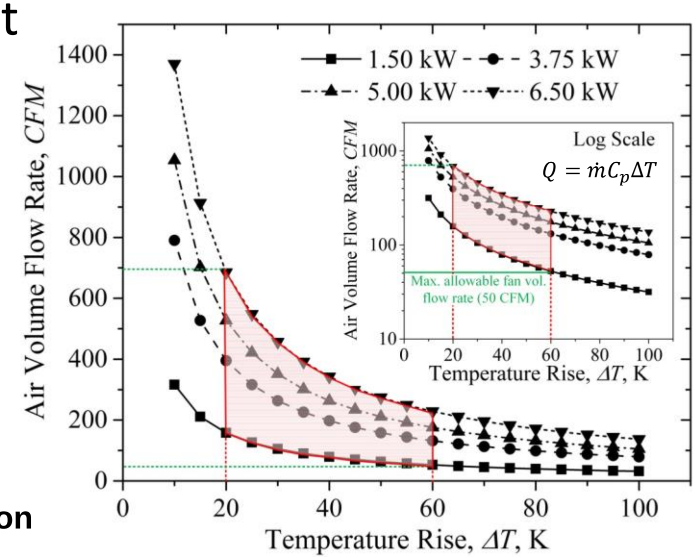
Air Cooling – Technology Breakdown

- Ultimate simplicity, but inherently poor coolant



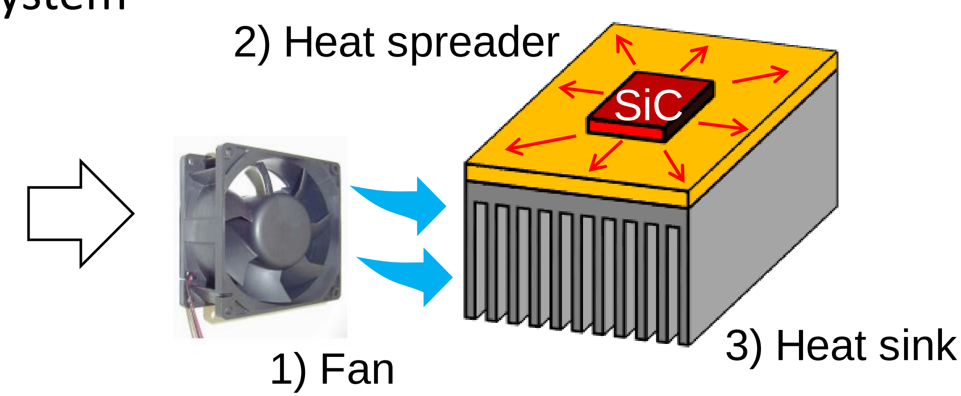
* Ref.: Kim, et al., 1996





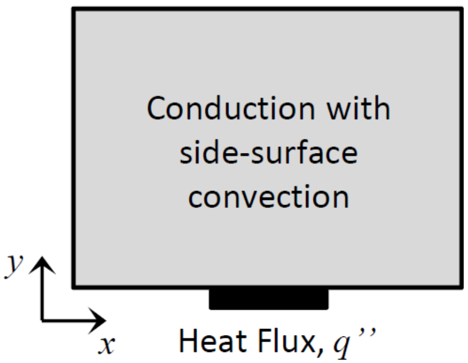
- Key technologies for air cooling system

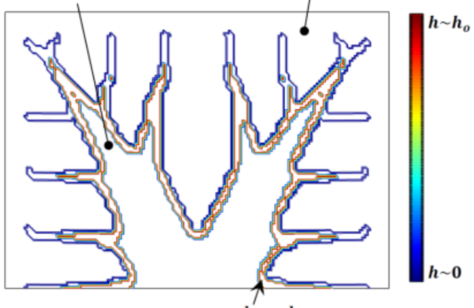
1) Efficient air movement
2) High performance heat sink
3) Extreme heat spreading

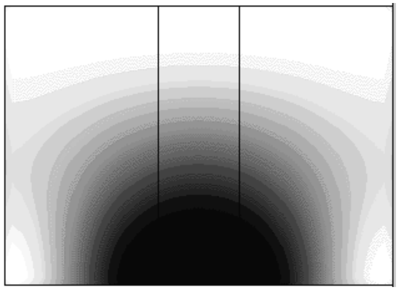


Air Cooling – High Performance Heat Sink

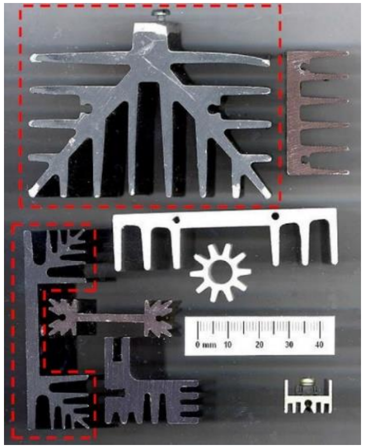
- Optimization of basic 2-D finned element





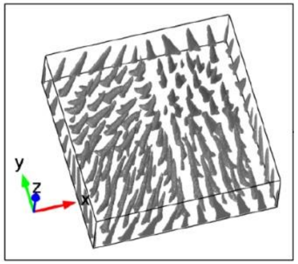


*Ref.: Dede, et al., 2015

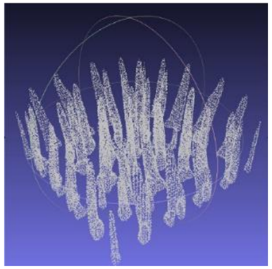


*Ref. : https://en.wikipedia.org/wiki/Fin_(extended_surface)

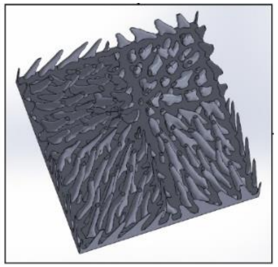
- Application to 3-D heat sink design



3D Optimization Result



Quarter-Symmetry Point Cloud Data

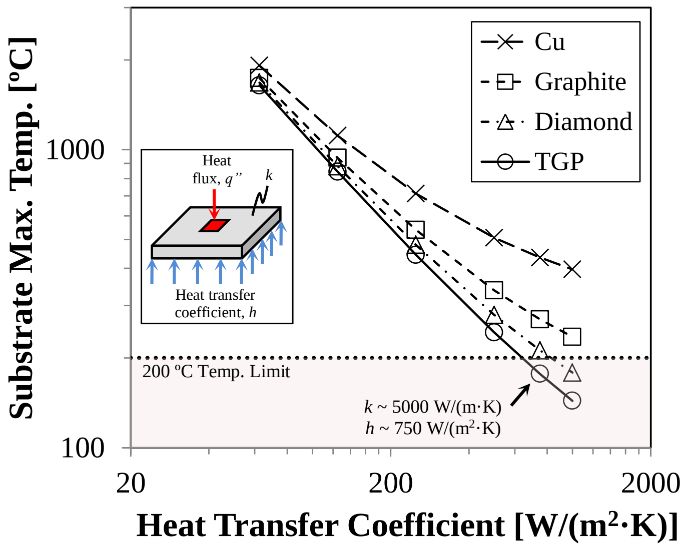


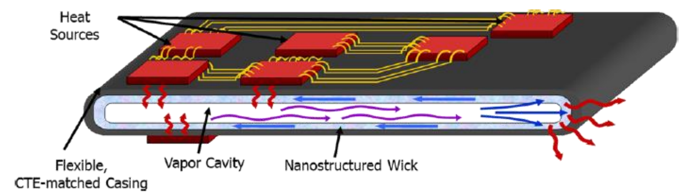
Solid Model CAD Geometry

AlSi12 Rapid Prototype

Air Cooling – Extreme Heat Spreading

- Efficient heat spreading required to utilize aggressive air cooling

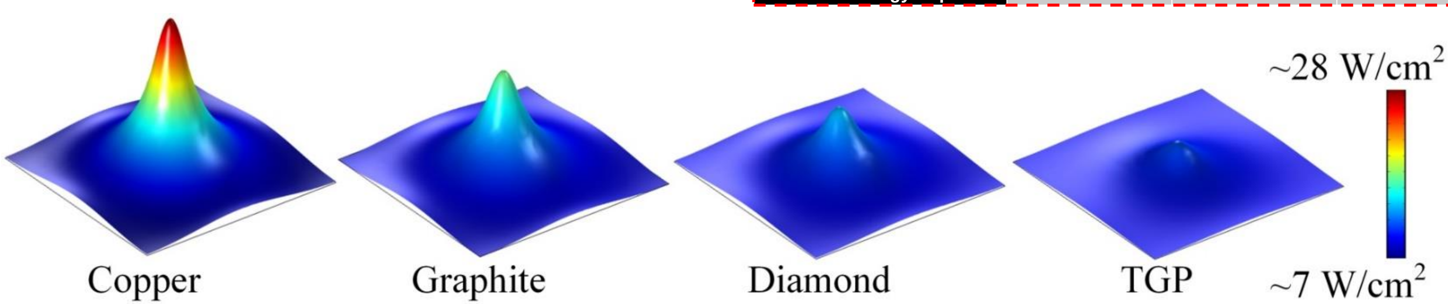




*Ref.: Bar-Cohen, et al., 2015

Thermal Ground Plane (TGP) Concept

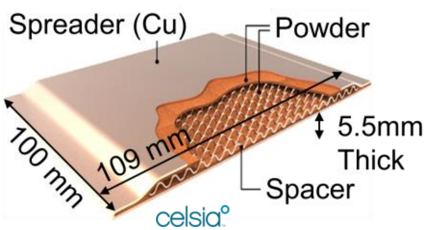
Evaporator Porous Structure		Maximum Heat Flux [W/cm²]		Superheat [K]		Heated Area [mm²]
Electrodeposited Cu [16]	Generally, increasing heat flux →	>1200	← Generally, increasing superheat	~10	← Increasing heated area	0.6
Cu µ-posts + nano-CuO coating [18]		~800		~35		4
Biporous silicon µ-posts [19]		~730		~13		~6
Sintered Cu [20]		~590		~23		25
Biporous sintered Cu [21]		~990		~147		32
Sintered Cu + feed arteries [17]		~580		~72		100
Technology Gap		> 1000		< 35		> 100

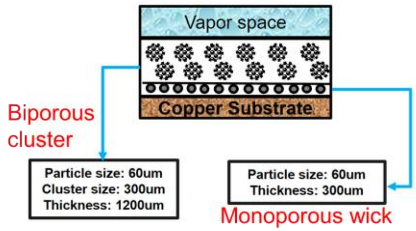


*Ref.: Dede, et al., 2016

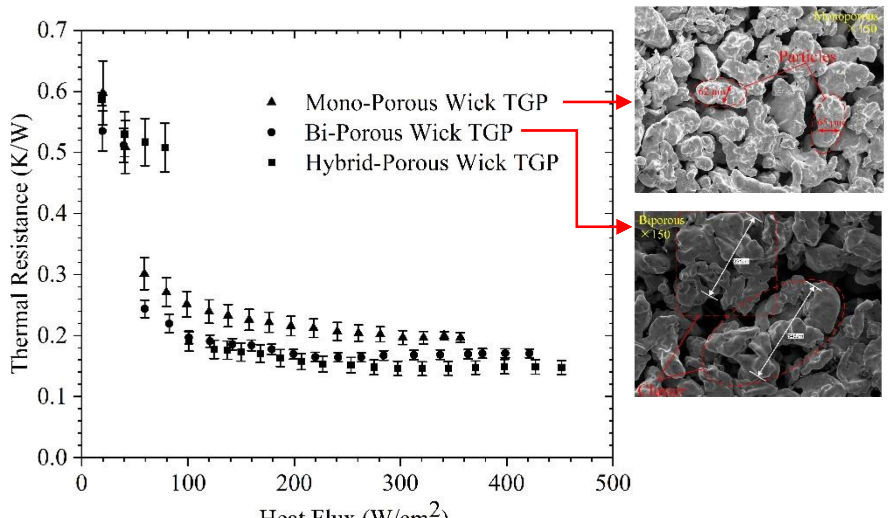
Air Cooling – Extreme Heat Spreading

- Novel wick structures to enable high heat fluxes



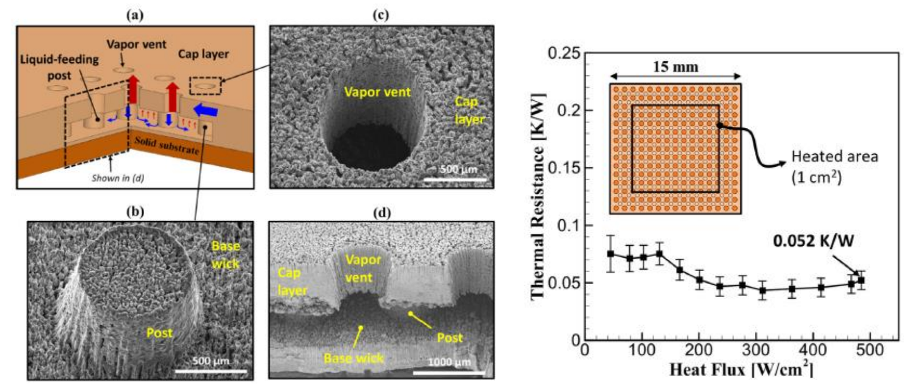


Vapor Chamber & Wick Design

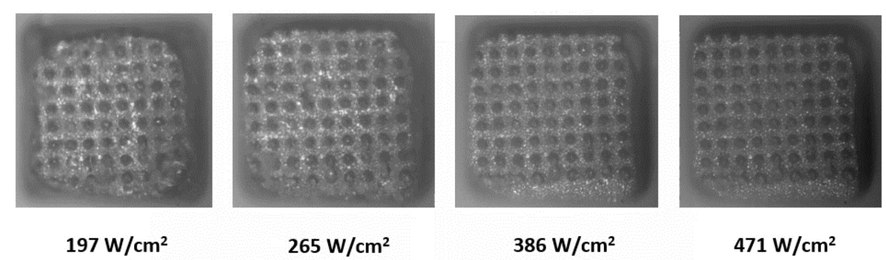


*Ref.: Zhou, et al., 2018

TGP Heat Flux vs. Thermal Resistance



*Ref.: Sudhakar, et al., 2019



*Ref.: Sudhakar, et al., In press

At high heat flux, liquid menisci recede to separate liquid feed and vapor vent mechanism

Wick Heat Flux vs. Thermal Resistance

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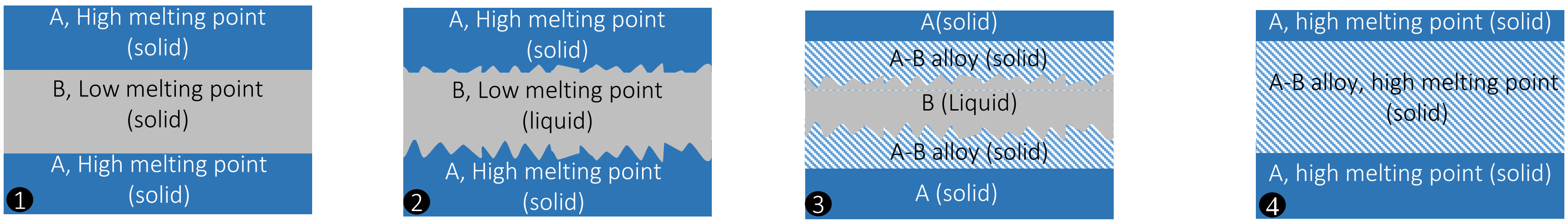
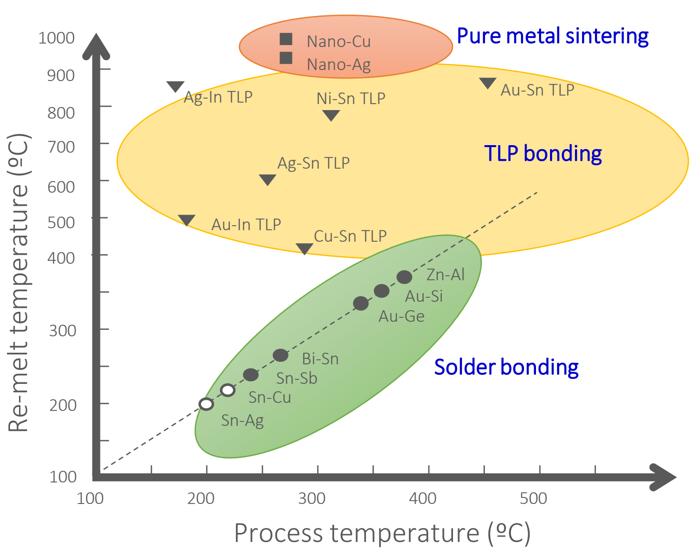
Transient Liquid Phase Bonding Overview

- Technology benefits



Assembly | Diffusion | Isothermal solidification | Homogenization



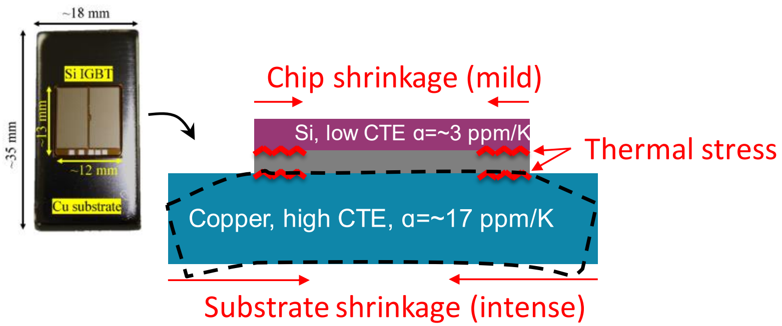
*Ref.: Noguchi et al., 2016

Candidates	Re-melting temp.	Process temp.	Fabrication difficulty	Material cost
Pure metal sintering	○	○	✖	✖
Solder bonding	▲	▲	○	○
TLP bonding	○	○	▲	○

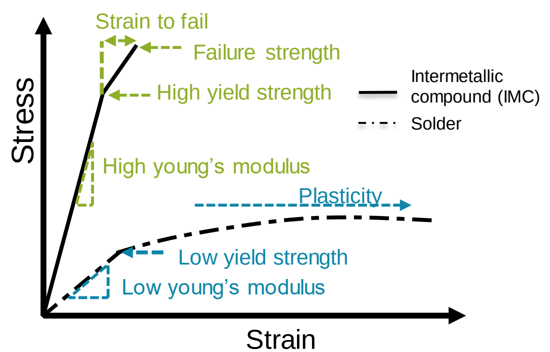
○ Good ▲ Moderate ✖ Bad

TOYOTA APEC

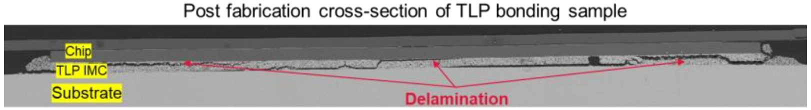
Die Attach Challenges & Higher Compliance Concept



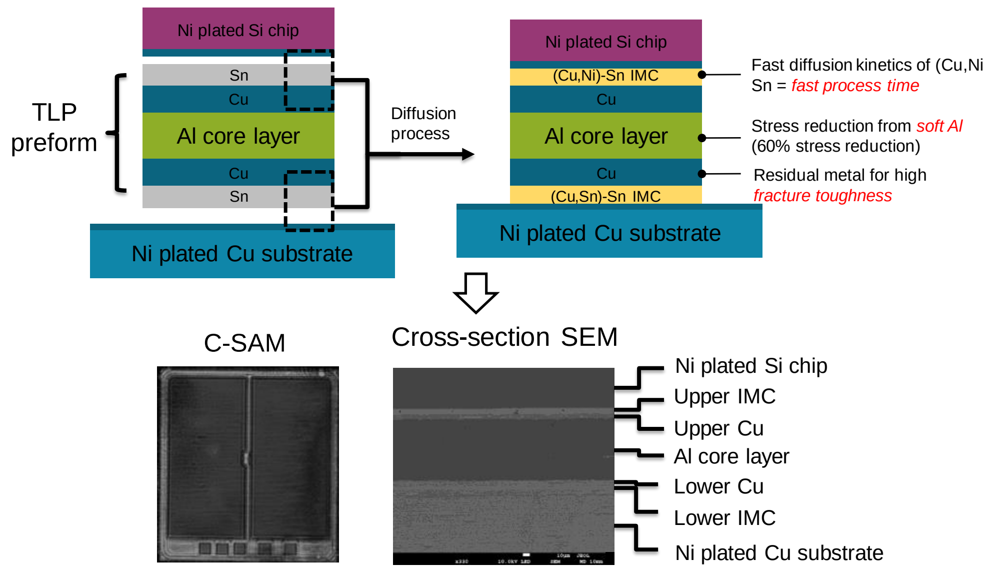
Copper Substrate Die-Attachment



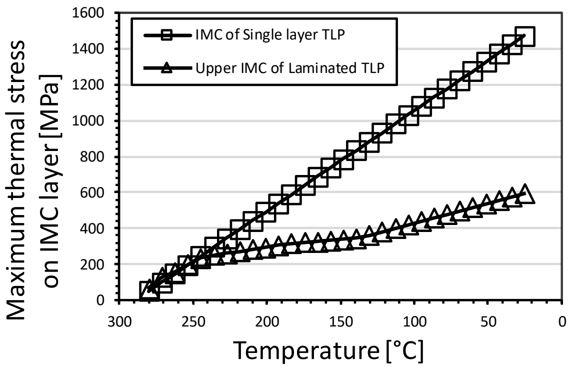
Post fabrication cross-section of TLP bonding sample



TLP IMCs brittle & susceptible to cracking



*Ref.: Liu et al., 2019

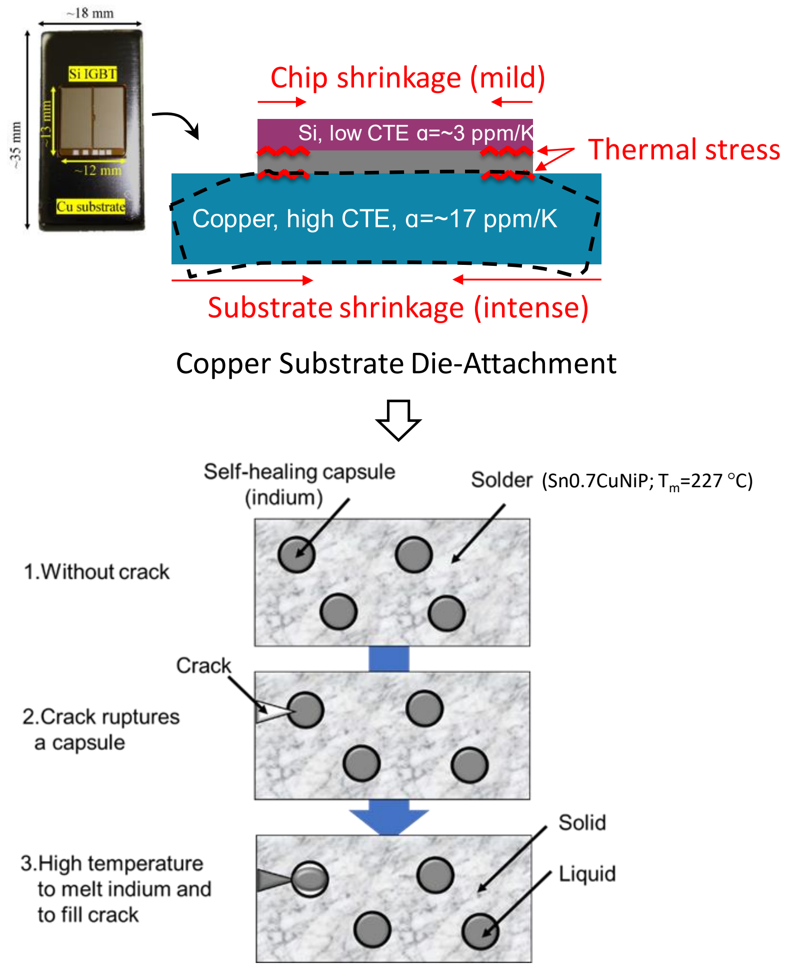


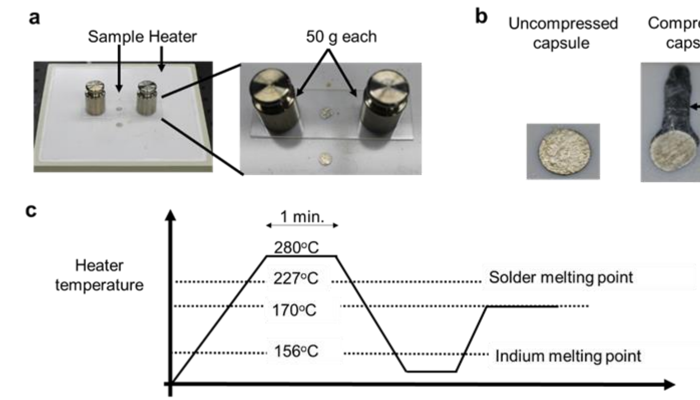
Introduce compliance via laminated preform w/Al core

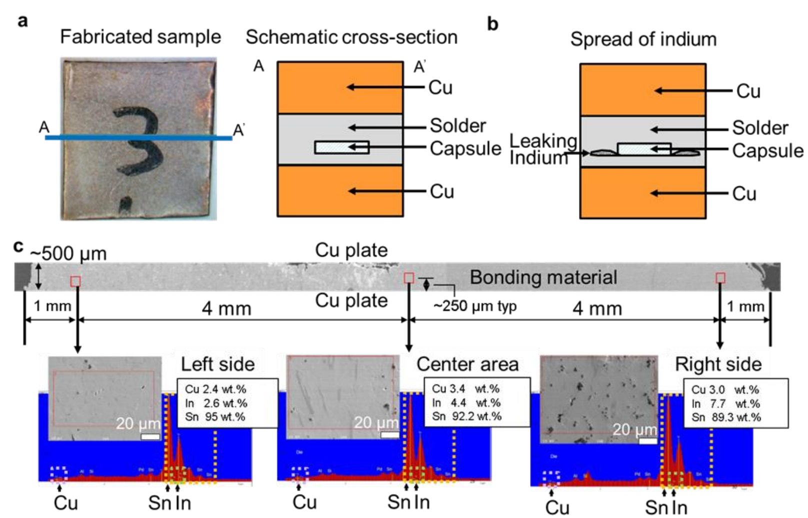
Overview

- Characteristics of Wide Band-Gap Devices
- Requirements of Next-Generation Packaging
- Packaging Trends for Power Electronics
- Relevant Future Technologies
  - Near-Junction Cooling
  - Thermal Ground Planes
  - Transient Liquid Phase Bonding
  - Self-Healing Die Attach
- Conclusions

Self-Healing Die Attach Concept







Atomic layer deposition (ALD) fabrication of In-Pt core-shell capsule for material system proof-of-concept

Overview

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Conclusions

- Higher power density requires consideration of embedding and integration
  - Remote cooling fundamentally limits order-of-magnitude size reduction
  - New packaging strategies and process workflows required
- Near-junction cooling explored as ultra-compact packaging paradigm
  - Straight channel and arrayed hierarchical unit cell flow structures explored
  - Unit cell design exhibits reduced pressure drop and higher heat transfer rates
  - Packaging explored as next step → heterogeneous integration
- Air cooling is robust and simple but requires effective heat spreading for high power density application
  - Heat sink optimization coupled with thermal ground plane technologies may be a solution
- High temperature operation bonding materials are critical
  - Transient liquid phase bonding with increased compliance has potential
  - Self-healing die attach may be disruptive technology to increase package reliability

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