Cooler Material Reliability Considerations for Bare Die Impingement Cooling in Package

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S-PACK Lab
(Advanced Packaging)

Symposium on Reliability for
Electronics and Photonics Packaging

HETEROGENEOUS INTEGRATION ROADMAP

The challenge of high-density heterogeneous integration: getting the heat out, so devices can operate reliably with a long lifetime.

- ➢ The Thermal Chapter of the HI Roadmap looks out 5 to 10 years, anticipating the needed development of cooling technologies
- ➢ You can download chapters from the Roadmap (free) at eps.ieee.org/hir
- ➢ For more detailed reliability aspects of electronics/photonics packaging, consider attending the **Symposium on Reliability for Electronics and Photonics Packaging**, Nov. 16-17 (in-person and virtual):

  attend.ieee.org/reppp

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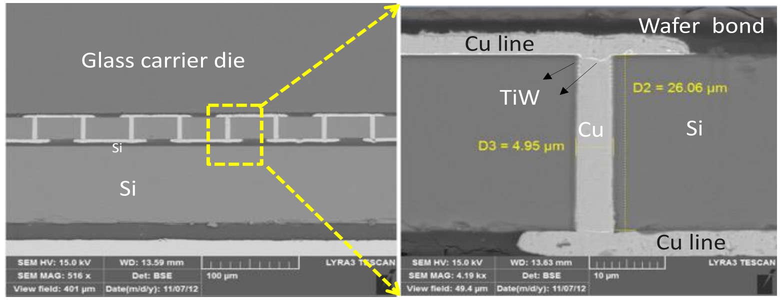
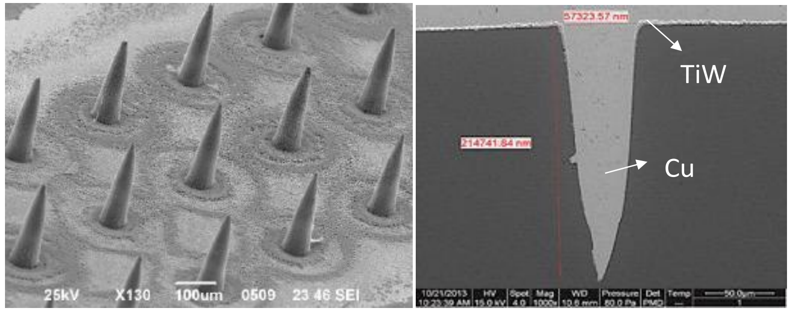
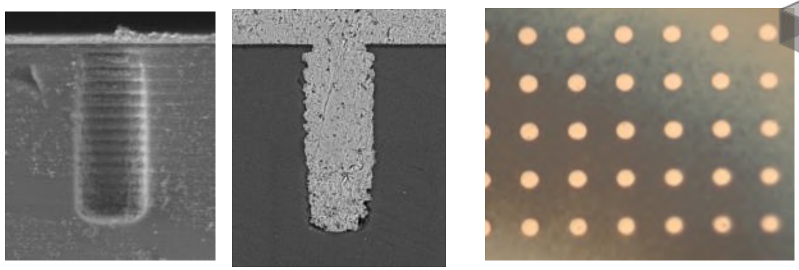
Topic 1: Materials, Processing, and Architecture Development for Semiconductor Packaging



Wei *et al., IEEE EMAP*, 2012: 1-5.



Wei, et al., IEEE EPTC 2014: 601-605.



3μm TSV from via etching and CMP

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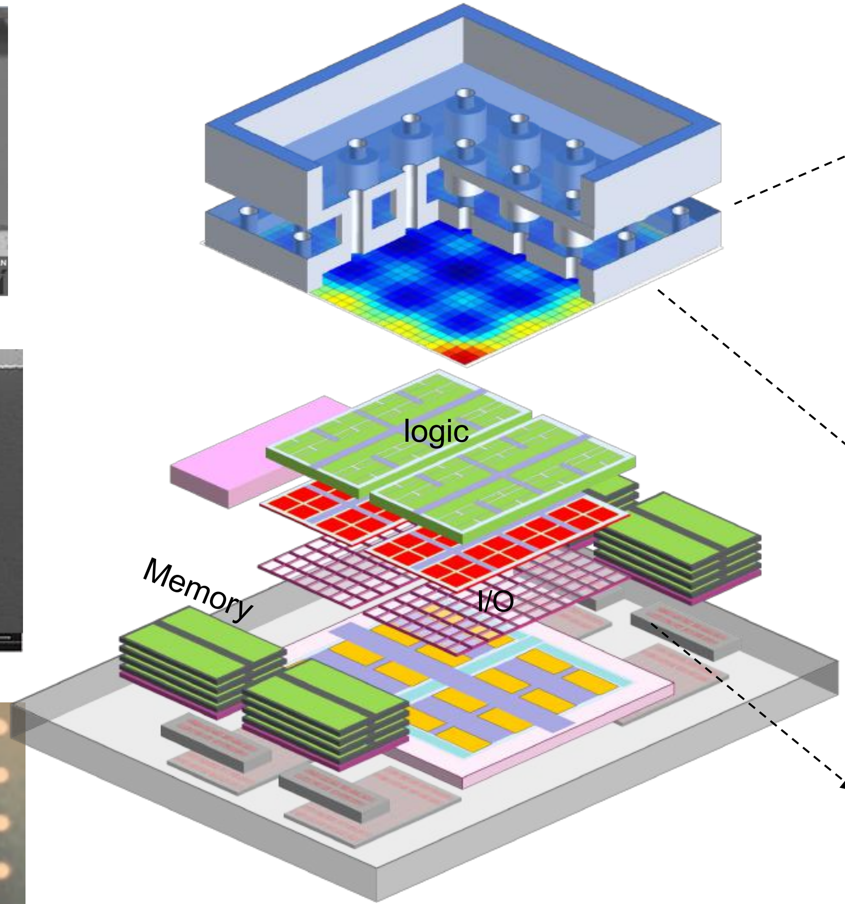
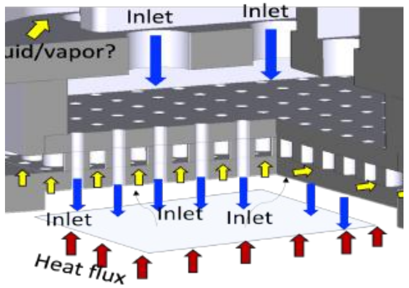
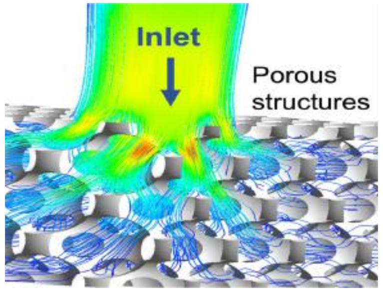
Topic 2: Chip and Package Level Electronic Cooling: Two-Phase Jet Cooling and Microchannel Cooling



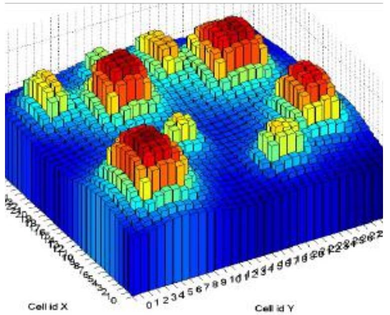
Chip and Package Level Electronic Cooling: Jet Cooling and Microchannel Cooling



Surface Engineering Enhancement of Advanced Cooling Technology



Thermal modeling analysis and management of advanced packaging



Key goal: Solving fabrication challenges in semiconductor packaging and assembly, and associated heat transfer problems

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OUTLINE

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  - Additive manufacturing polymer-based cooler
  - CTE modified polymer-based cooler
  - Glass-based cooler
  - Metal 3D-Printed Direct Liquid Jet-Impingement Cooling
  - Ceramic-based on cooler
- Other cooling reliabilities: clogging, corrosion…

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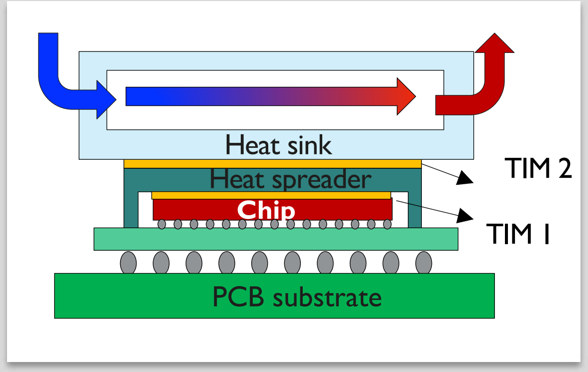
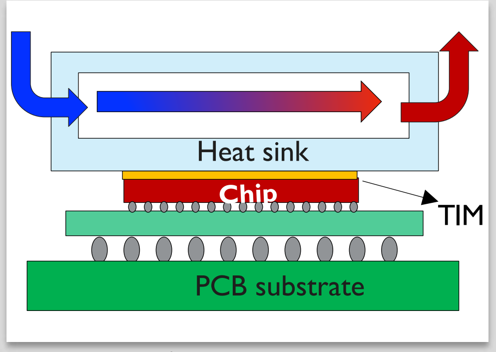
State of the art liquid cooling for high performance system

Liquid cooling with Thermal interface material: TIM

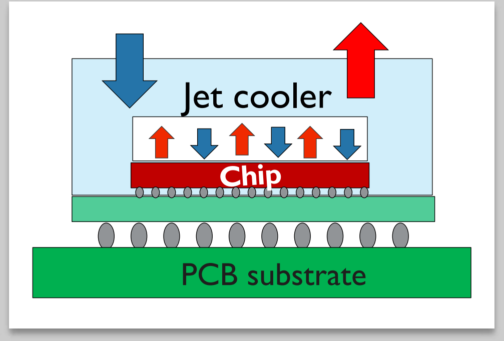


A: Liquid cooling + heat spreader (metal lid) with TIM I and TIM 2

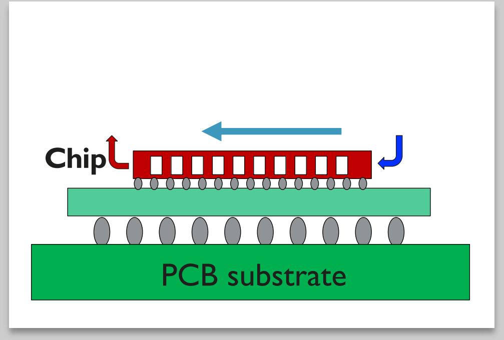


B: Directly attached liquid cold plate with TIM I

Direct Liquid cooling on top of the chip backside



C: Bare die backside jet cooling



D: Embedded microchannel cooling inside the die

<u>Direct liquid jet cooling on the chip</u> can eliminate the thermal resistance of thermal interface material!

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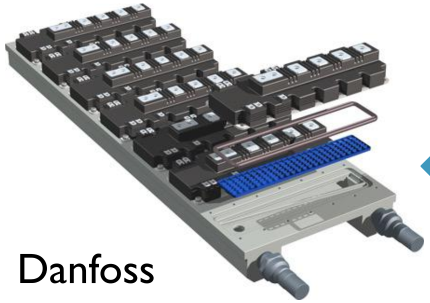
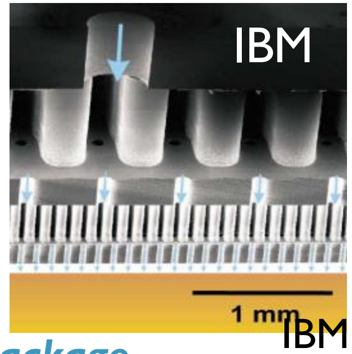
Bare die impingement cooling in package

Existing technology options:

Module level cooling — *Si processing techniques*

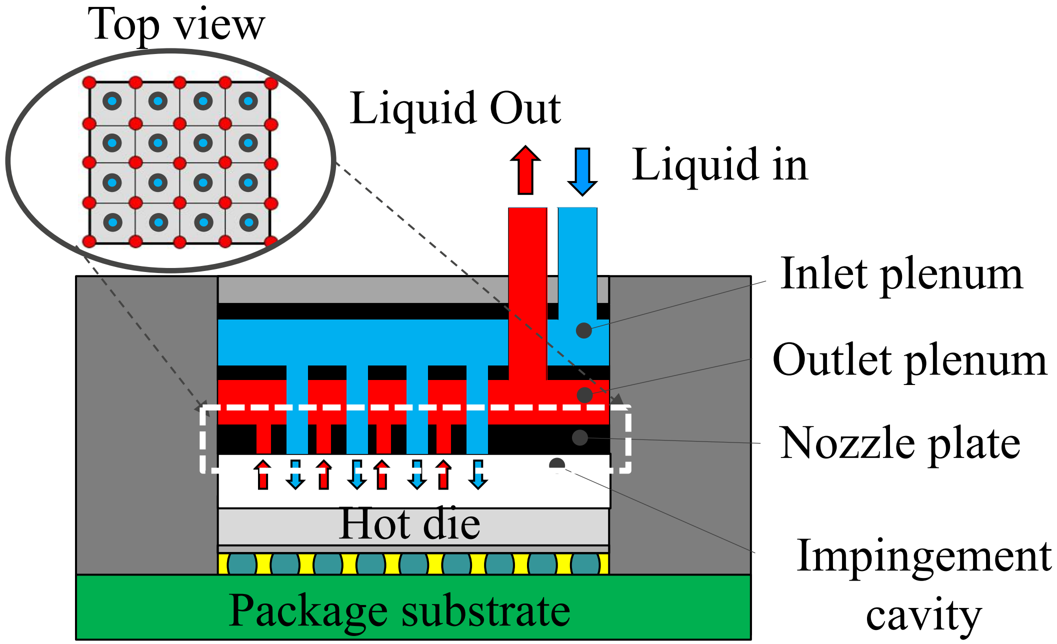




Bare die impingement in package

Our target:

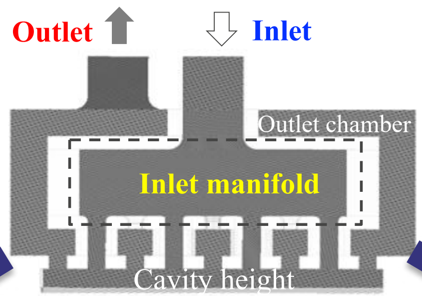
- **Customizable** nozzle array to match chip power map
- **Low-cost** fabrication method: 3D printing
- Goal: one part solution - cooling integrated **in chip package**



Advantages:

- Direct cooling → Eliminate TIM thermal resistance
- Parallel type cooling → Reduce temperature gradient
- Deliver high localized heat transfer rates → Hotspot targeted cooling
- Multiple jet array → Temperature uniformity

Modeling methodologies for optimal cooler design

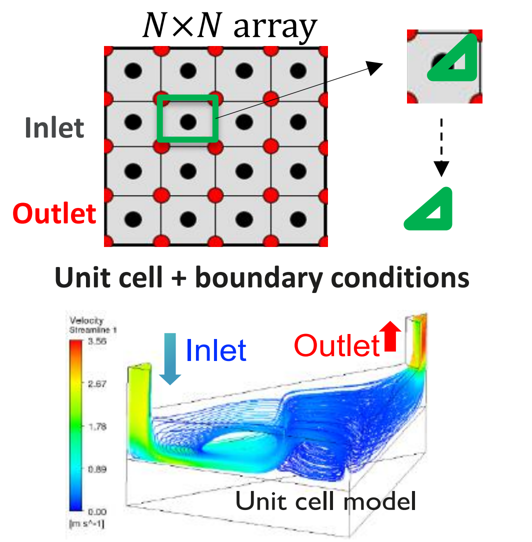


Objective: Understanding the thermal/fluidic behaviors using CFD modeling

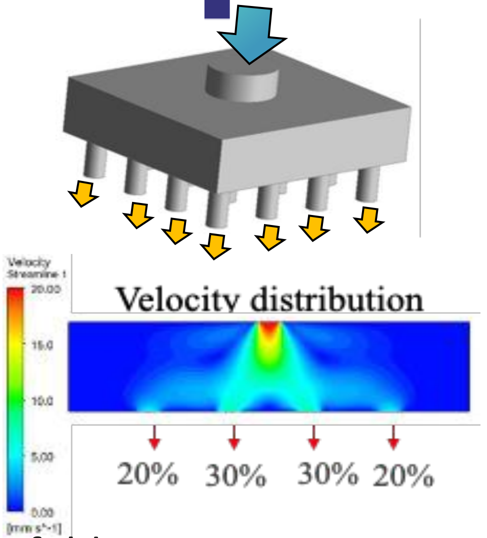
(1) Unit cell-level

(2) Manifold-level

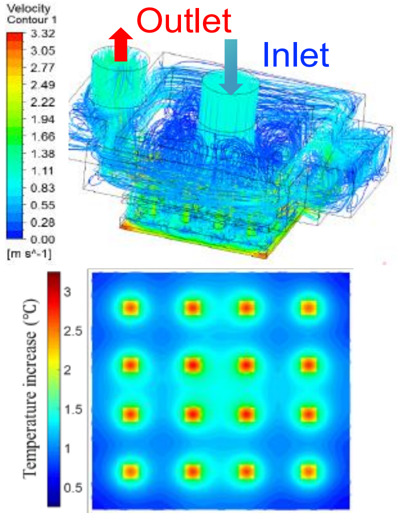
(3) Full scale cooler level



Used for extensive DOE for the nozzle pattern optimizations and dimensionless analysis



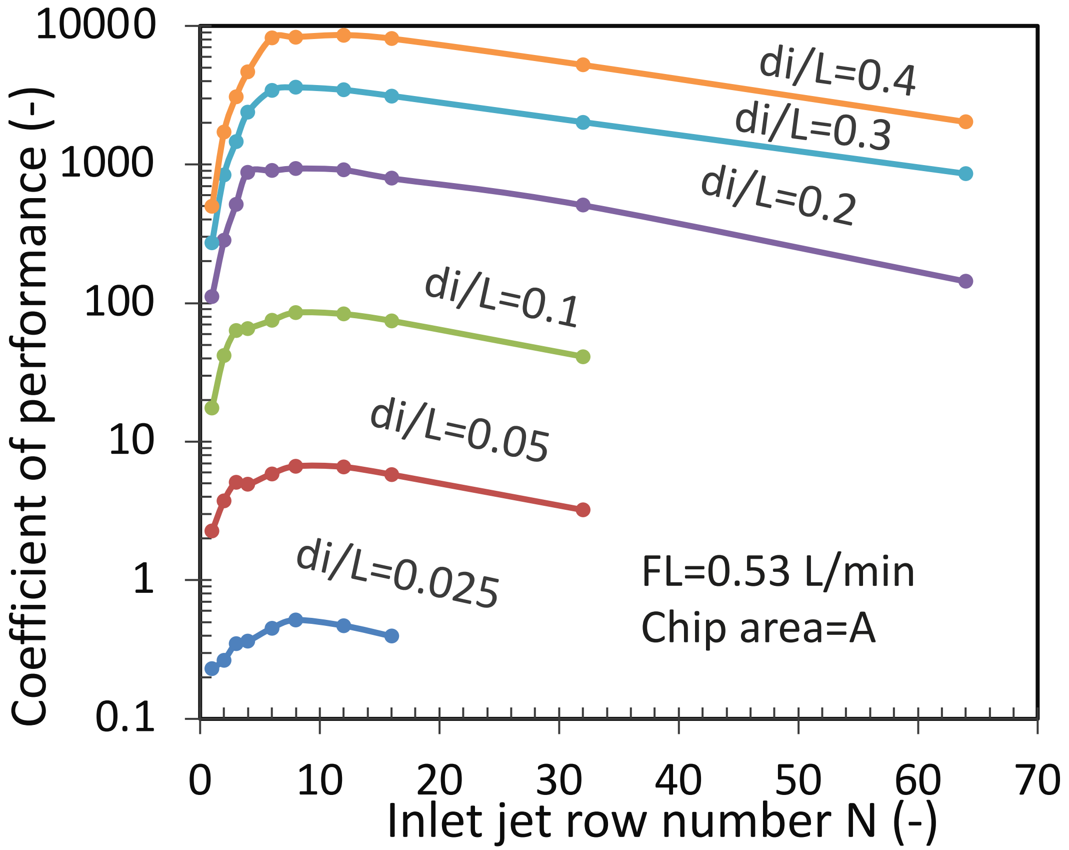
Manifold geometry optimization for better flow uniformity and lower pressure drop



Provide system level pressure and temperature distribution information for cooler design

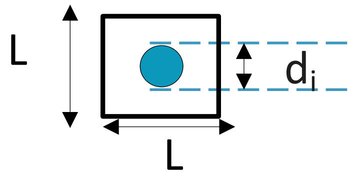
Unit Cell model modeling → Larger diameter

Wei *et al., Appl. Therm. Eng.*, 2020: 115767.



Coefficient of performance:

$$COP = \frac{Cooling\ Power}{Required\ pump\ power} = \frac{Max\ allowed\ temp\ increase/R_{th}}{Required\ pump\ power}$$



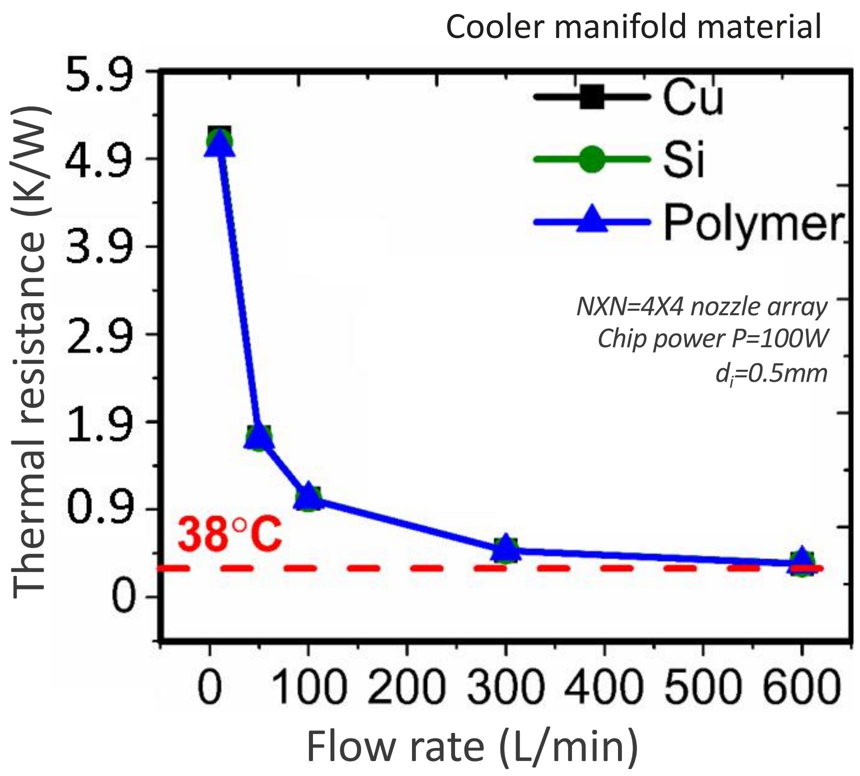
d_i/L: inlet diameter ratio

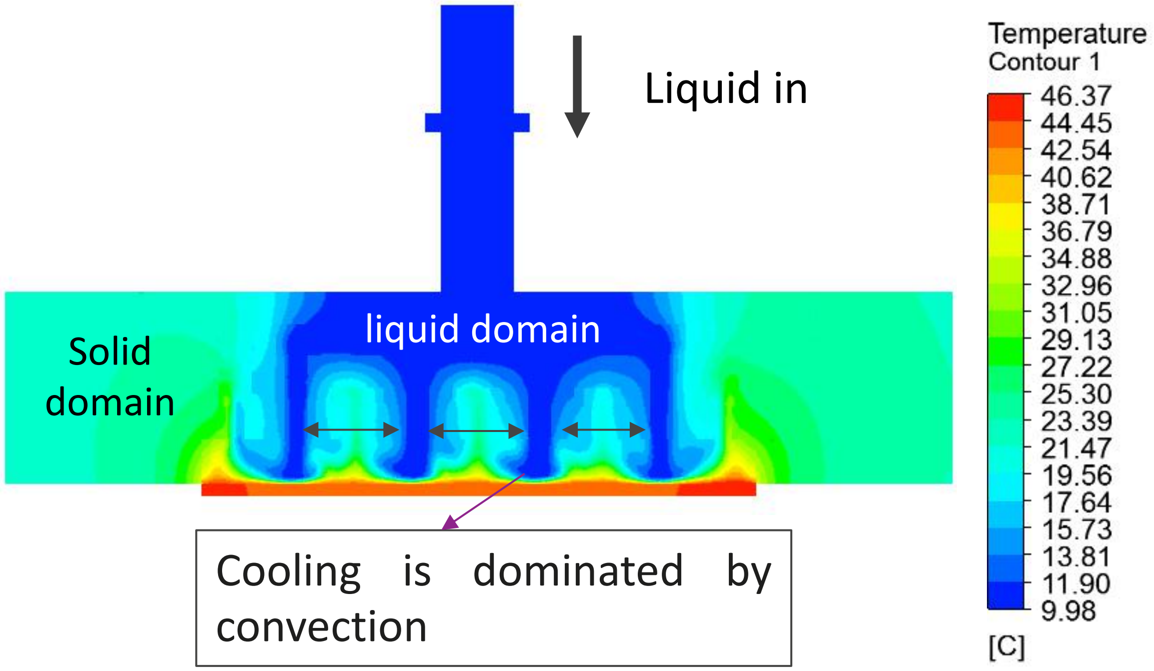
N×N: total inlet jet number = A/(L*L)

For a constant flow rate:

- Higher inlet diameter ratio d_i/L has larger COP
- Inlet nozzle number N between N=6 and N=8 shows optimal COP
- Making the required diameters compatible with **additive manufacturing** fabrication methods

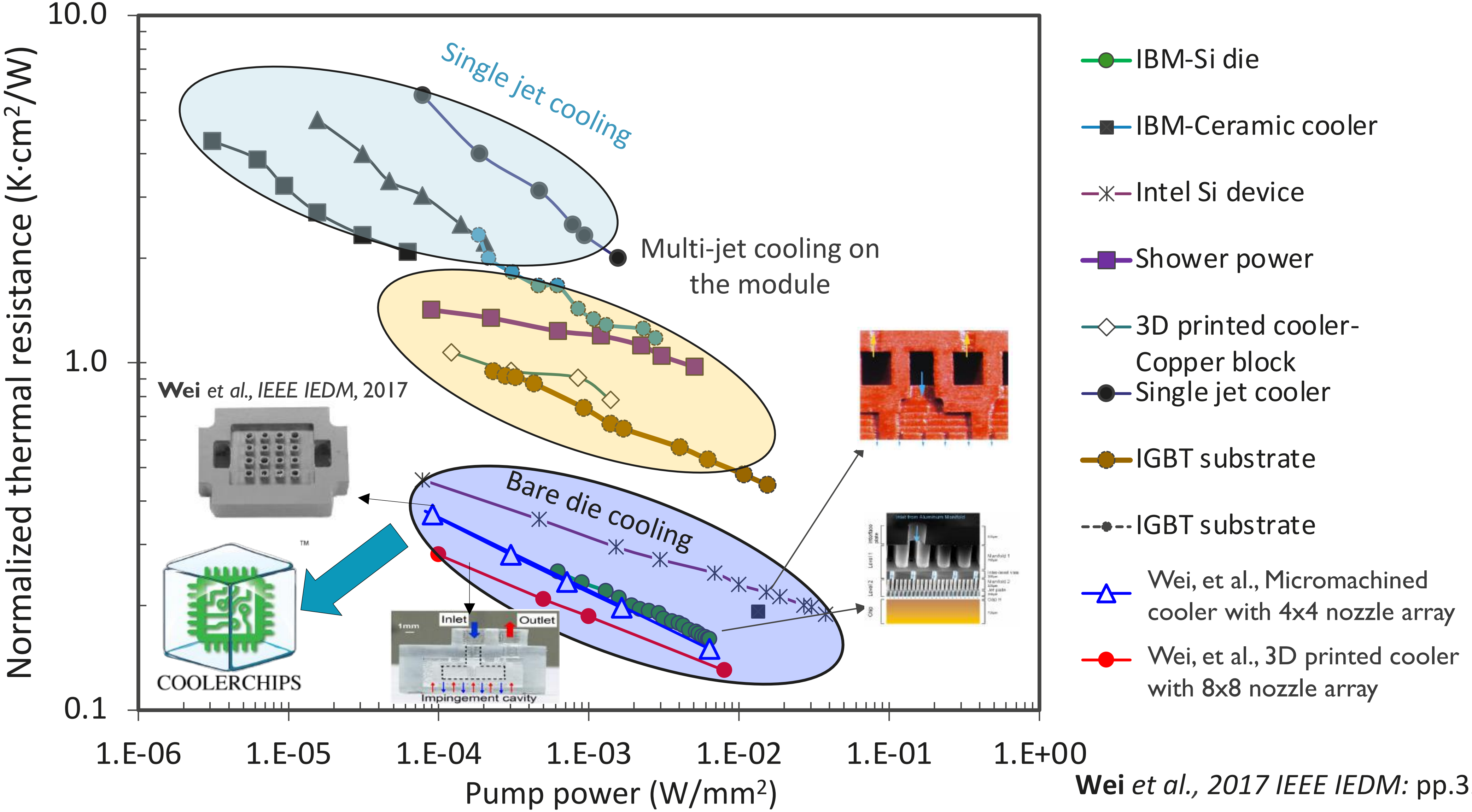
Full cooler level modeling → cooler material





- Negligible impact of cooler material thermal properties
- Enables low-cost fabrication technologies → polymer-based jet cooler

Bare die microjet cooling in packaging benchmarking



Wei *et al., 2017 IEEE IEDM:* pp.32-5.

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Cooler reliability considerations

During cooler assembly

- Cooler assembly options:
  1. First assemble package to board, then mount cooler on package (glue, clamping, ...)
     → No harsh temperature requirement for cooler material
  2. First mount and seal cooler on package, then assembly package with cooler on PCB
     → Cooler assembly needs to survive reflow temperature (250°C)
- Property: Heat deflection temperature HDT

  **the temperature at which a plastic deforms under a specified load (e.g. 0.45 MPa)*

Ideal material: HDT > 250°C

During cooler operation

- High reliability required for thermal cycling
- Property: Coefficient of thermal expansion CTE

Ideal material: CTE matched with package substrate

Polymer based 3D printing (1)

Stereolithography (SLA) used for fabrication of demonstrators

- UV exposure of ***liquid resin*** (acrylic based thermosetting polymer)
- Material: Somos Watershed UX 11122 (DSM) (link)
- Typical properties do not meet requirements
  - CTE: 100 – 150 ppm/°C
  - HDT: 45 – 60°C
- Recent material developed:

  Formlabs FLHTAM01 High Temp Resin (link)
  - Interesting properties:
    - HDT: **289°C**
    - Other properties similar to Watershed material

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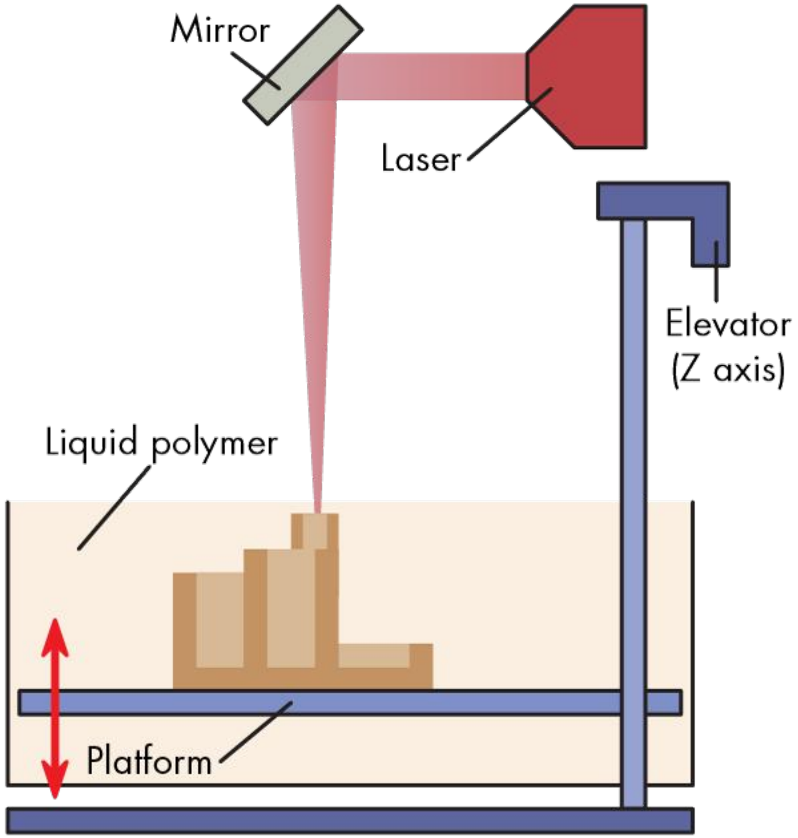


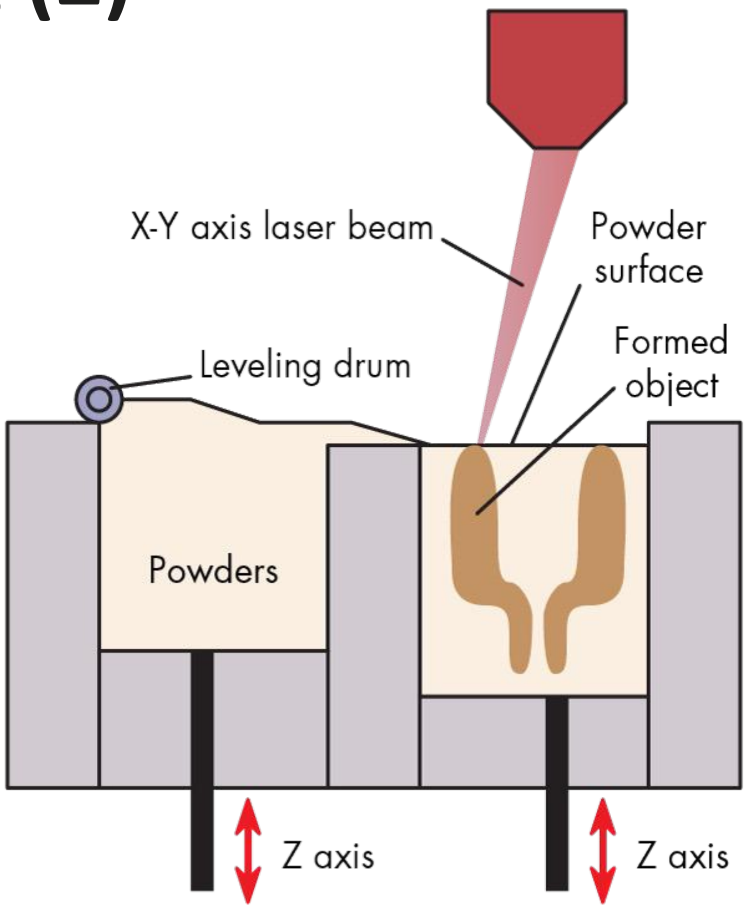
Stereolithography (SLA)

Source: What's the Difference Between Stereolithography and Selective Laser Sintering?

Polymer based 3D printing (2)

Selective laser sintering (SLS) can be alternative:

- Laser sintering of ***polymer powder*** (thermoplastic polyamide)
- Based on Nylon / polyamide polymers
  - Typical HDT ~ 150°C
  - Improvements: Aluminum filled PA (Alumide): HDT 169°C, Glass filled PA: HDT 176°C
- Previously not considered due to water absorption
- Recent new material development: Solvay AV-755 (link)
  - PAEK (polyaryletherketone)
  - HDT **278°C**
  - Very low water absorption of 0.01%
- Typical challenge for SLS: surface finish
- Interesting material to try out for demonstrator

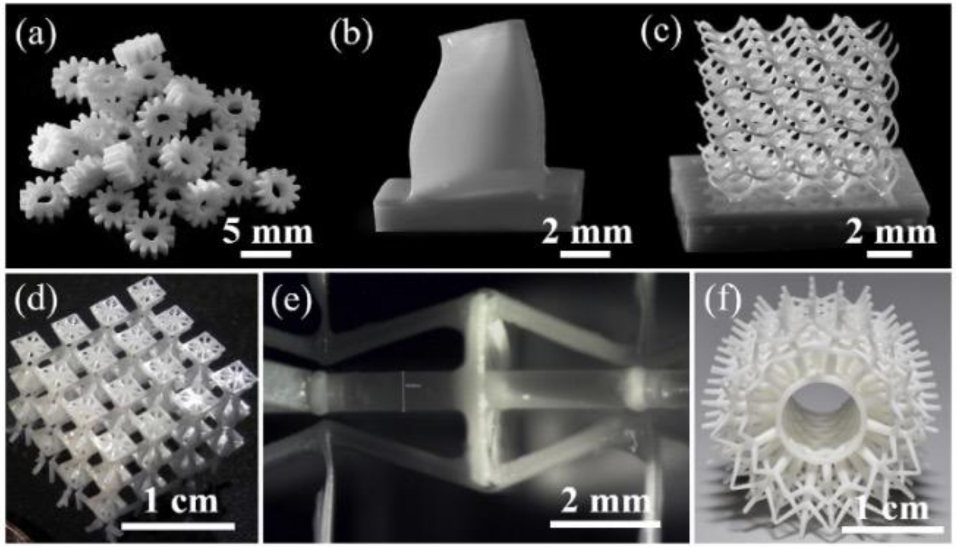


Selective laser sintering (SLS)

Source: What's the Difference Between Stereolithography and Selective Laser Sintering?

Other materials considered for 3D printing

- ***Ceramics*** can be used for high precision fabrication with good surface finish:
  - Slurry based photo-polymerization (*SLA, DLP, TPP*) with SiO_2, Al_2O_3, ZrO_2 or SiC show great potential for small scale fabrication with controllable feature size and surface finish
  - Demonstration of 3D microstructures with sub-μm resolution
  - Power based fusion (*SLS, SLM*) still under development
  - Very high temperature resistance: +1400°C
  - Interesting option to explore with printing partner
  - More expensive than polymer fabrication

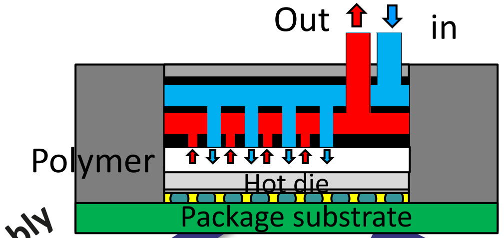


Source: ZhangweiChen, et al., 3D printing of ceramics: A review, Volume 39, Issue 4, April 2019, Pages 661-687

- Additive manufacturing with ***metals*** also allows very high temperature resistance:
  - Ti: 1660°C
  - Al: 1250°C
  - Stainless steel: 1400°C

Previous work: bare die impingement in package

Manufacturing strategies



Integrated the polymer-based jet cooler into the package

Cooler assembly with fixture

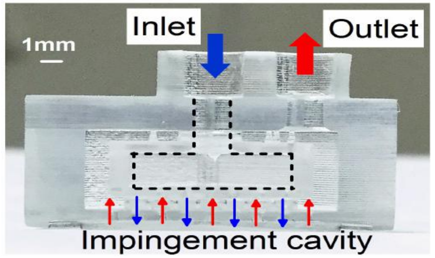
Direct on substrate

Proof of concept and fundamental study

CTE matched with the organic substrate

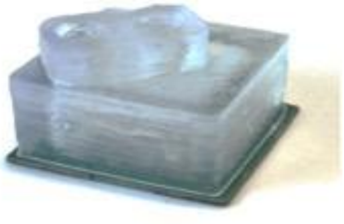
Micromachining cooler
(4X4 jet array nozzle diameter: ~500 μm)

Wei *et al., IEEE IEDM*, 2017



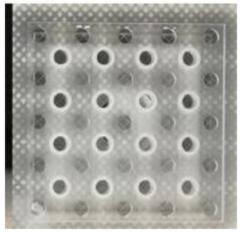
3D printing polymer cooler
(8x8 array nozzle diameter: 300 μm)

Wei *et al., IEEE ECTC*, 2018



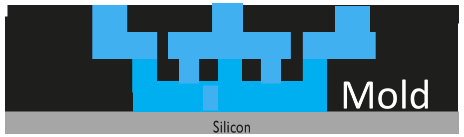
On-substrate direct printing cooler

Fei, Wei *et al.*, 2019 *SFF Symposium*



Glass cooler with low CTE

Wei, *Ph.D. thesis, 2020*



Cooler using injection molding and 3D printing sacrificial structure

Patented (Eric Beyne, imec)

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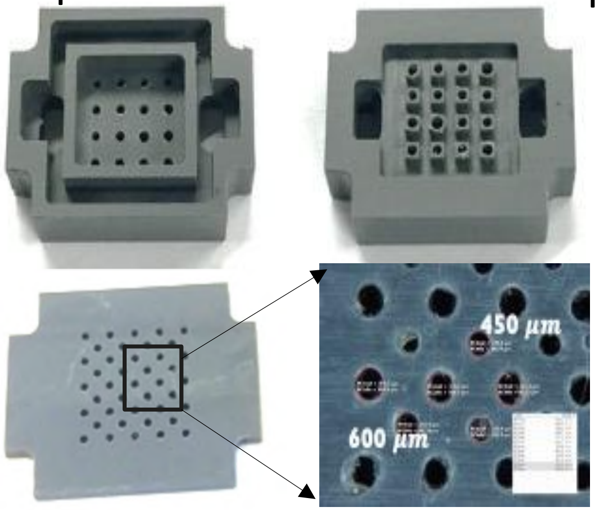
Novel 3D-shaped polymer multi-jet impingement cooler

Wei *et al., 2017 IEEE IEDM:* pp.32-5.

Top-> Bottom　　Bottom → Top

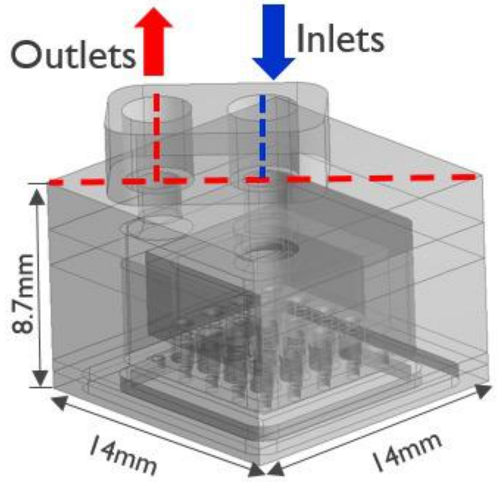


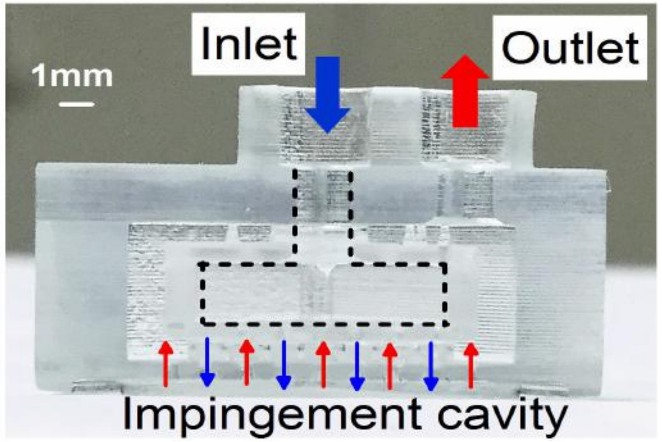
First demonstration of a low-cost polymer-based impingement jet cooler, reported in IEDM 2017

- 4×4 inlet jet array
- 5×5 outlet jet array
- 450 μm inlet nozzles diameter
- Mechanical machining

Wei *et al., IEEE Trans. Compon. Packag. Manuf. Technol*, 2019 9(9): 1815-1824.

materialise
innovators you can count on





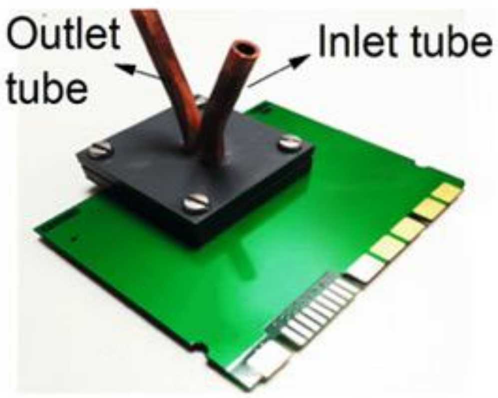
Advantages:

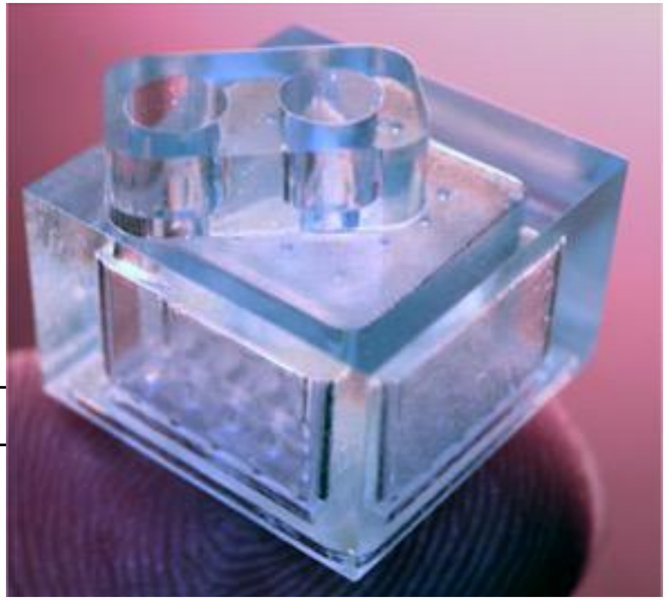
- Small form factor
- More flexible and customizable design
- Finer resolution of the internal structures

Challenges:

- Excess liquid resin removal
- Material compatibility with coolant
- Structural integrity → bridging of cavities

3D printed impingement jet cooling: package level size

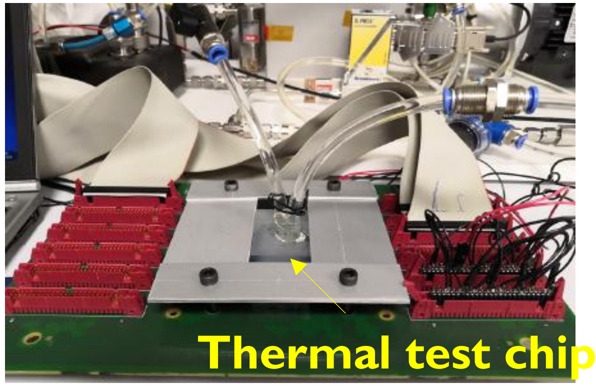


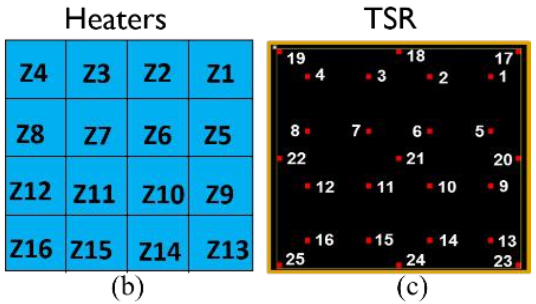


Geometry		Micromachined cooler	3D printed Cooler
Nozzle array	N	4×4	4×4
Inlet chamber height		3 mm	2.5 mm
Inlet diameter	d_i	0.45 mm/0.65mm	0.57 mm
Outlet diameter	d_o	0.6 mm	0.57 mm
Cavity height	H	0.6 mm	0.6 mm
Nozzle plate thickness	t	1 mm	0.55 mm
Cooler size	x,y,z	46×46×13 (mm^3)	18×18×8.7 (mm^3)

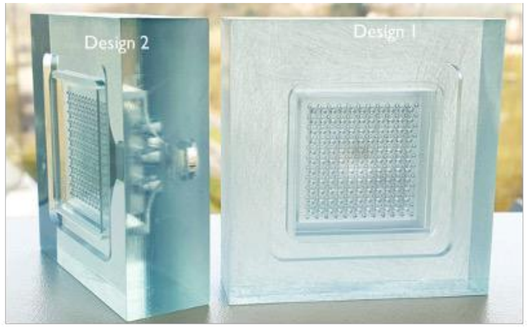
6.5X area reduction

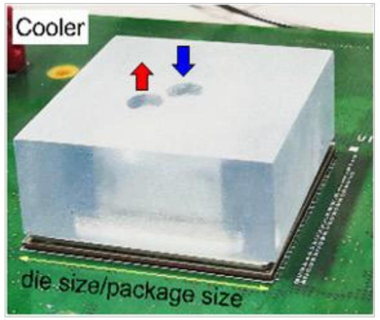
Bare die impingement in high-power, large size chip package

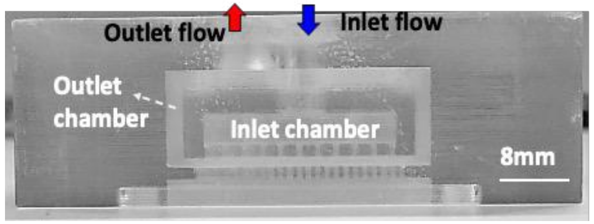




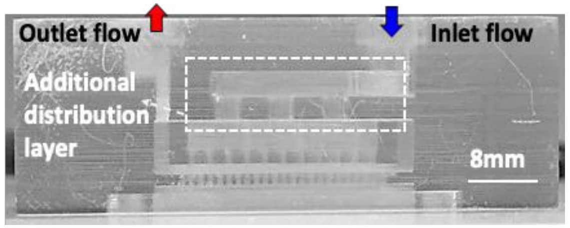
23×23 mm^2 test vehicle



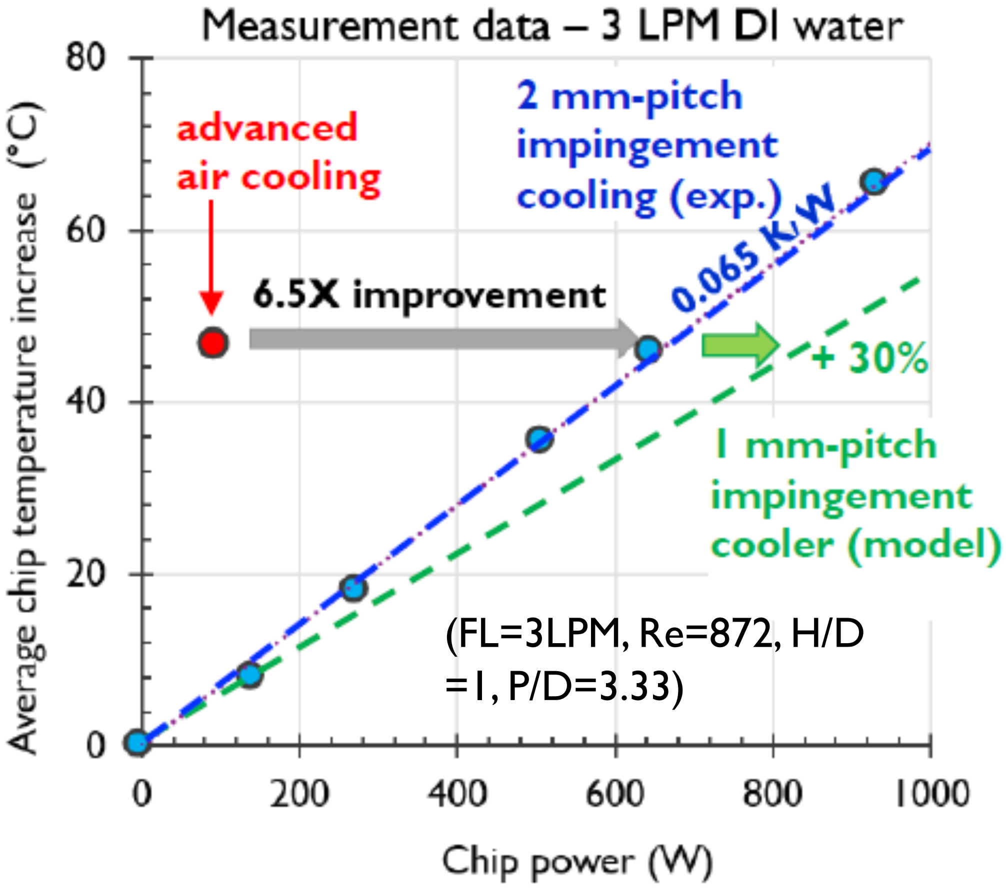




Design 1 with nozzle array below coolant entrance connection



Design 2 with additional distribution layer to improve flow uniformity over chip surface

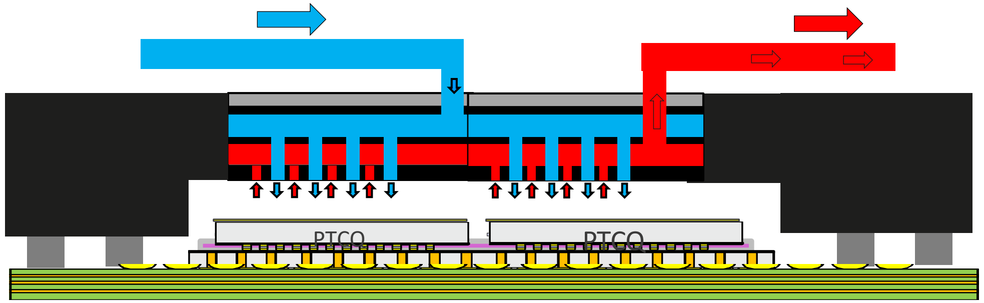


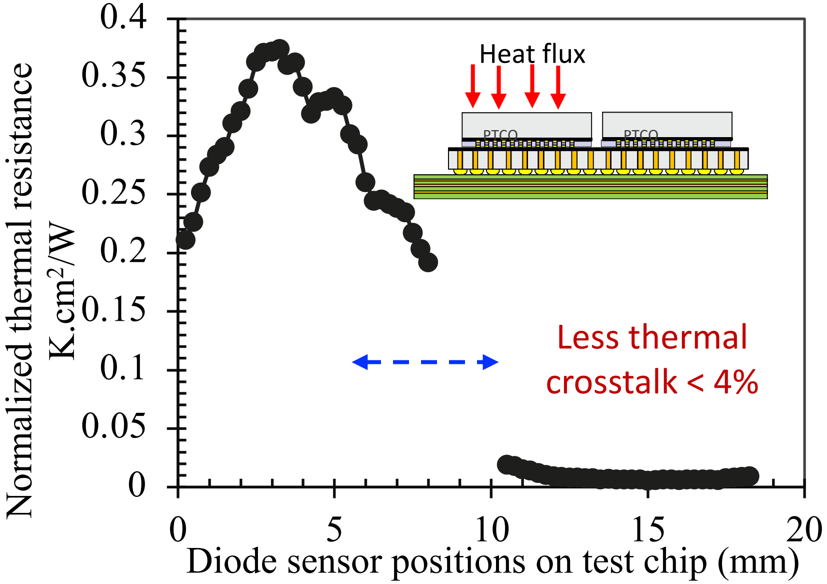
High power measurement with 1kW for 2mm inlet nozzle pitch, corresponding to a chip power density of 175 W/cm^2 → The average thermal resistance of the cooling with 3 LPM is 0.065 K/W.

Wei et al., *IEEE Trans. Compon. Packag. Manuf. Technol*, 2021: 415-425.

3D printing cooling for different packaging designs

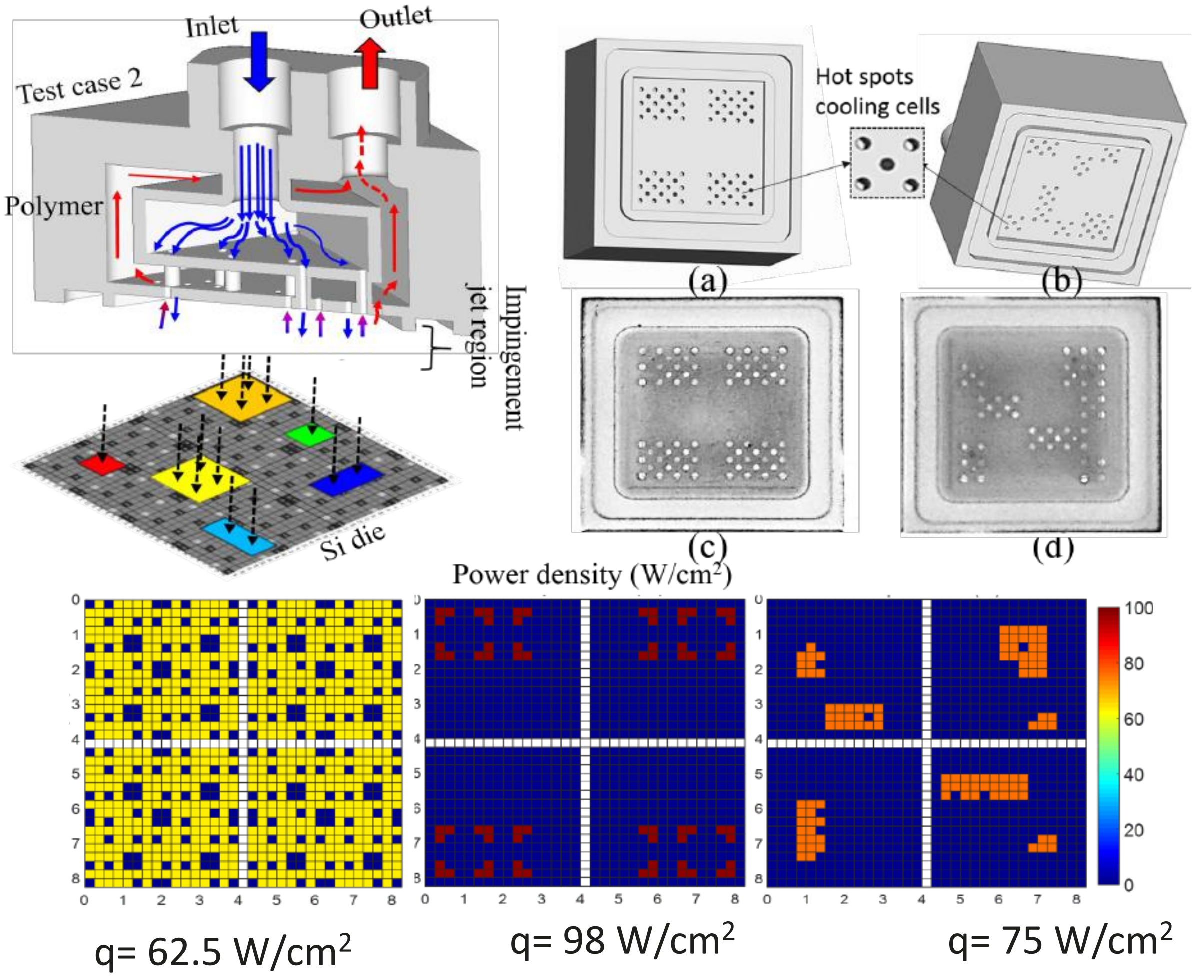
2.5D interposer packaging





Wei *et al.*, Appl. Therm. Eng., 2020, 164, 114535.

Hotspots targeted cooling



Wei *et al., IEEE Trans. Compon. Packag. Manuf. Technol,* 2020: 577-589.

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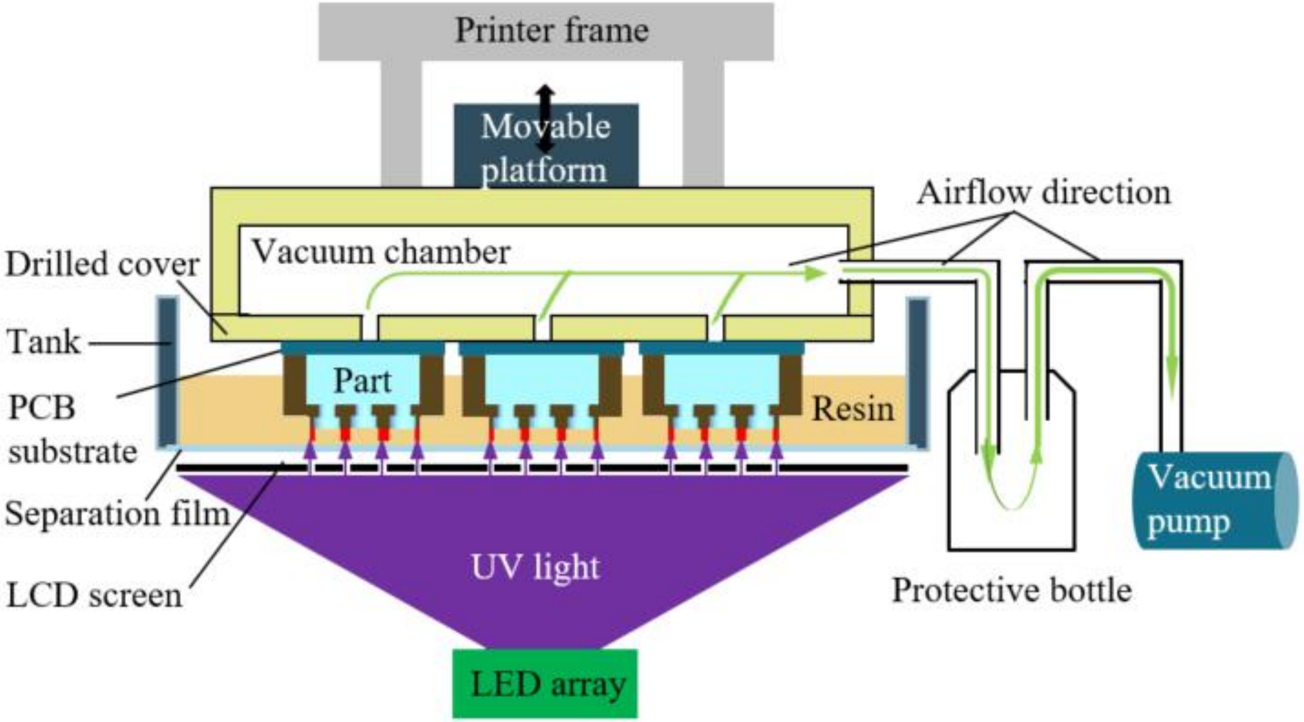
- Other cooling reliabilities: clogging, corrosion…

Additive manufacturing on printed circuit board (PCB)

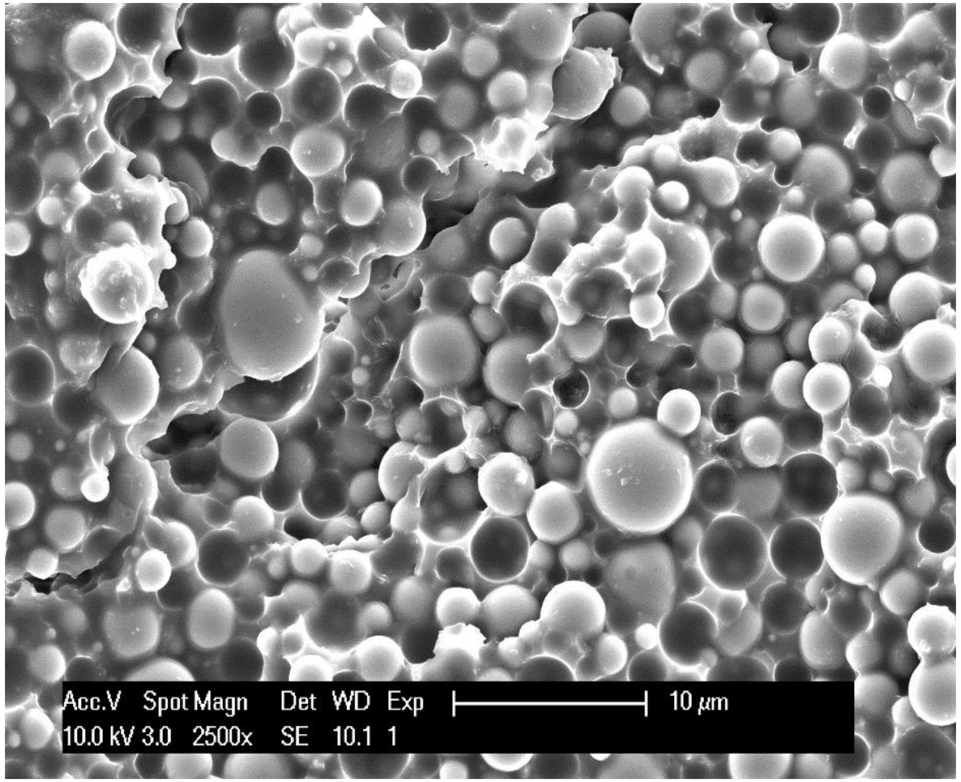


The bottom-up LCD-based stereolithography machine with a vacuum suction system (includes the vacuum chamber, the protective bottle and the pump)

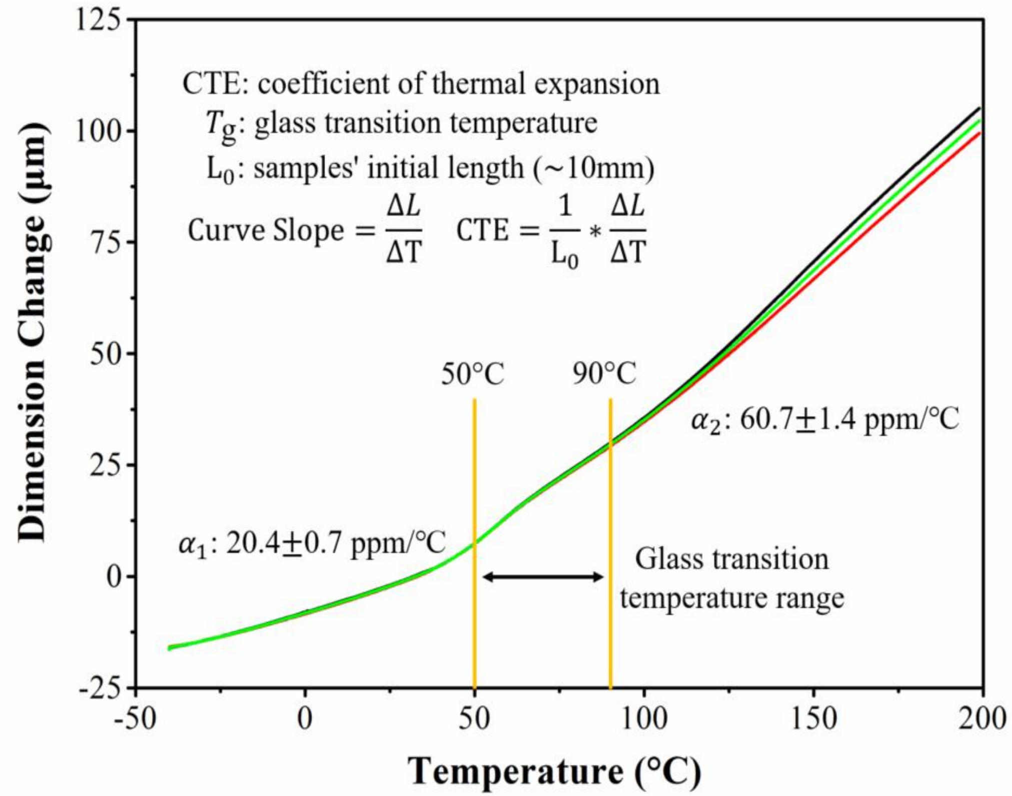
Fei, Wei *et al.*, 2019 *SFF Symposium*

- Need for **lower CTE polymers** due to current large mismatch with laminate CTE
- Collaboration with KU Leuven to develop the low CTE materials
- Trials with materials with lower CTE
  - **Silica and ceramic fillers** added to lower CTE
  - Limited filler concentration to keep material printable
- **Stereo-DIC technique** was used to measure the CTE of four composite materials for 3D printing of impingement cooler.

CTE modified polymer cooler with resin-silica composite



The microstructure of resin-silica composite printed at 25°C

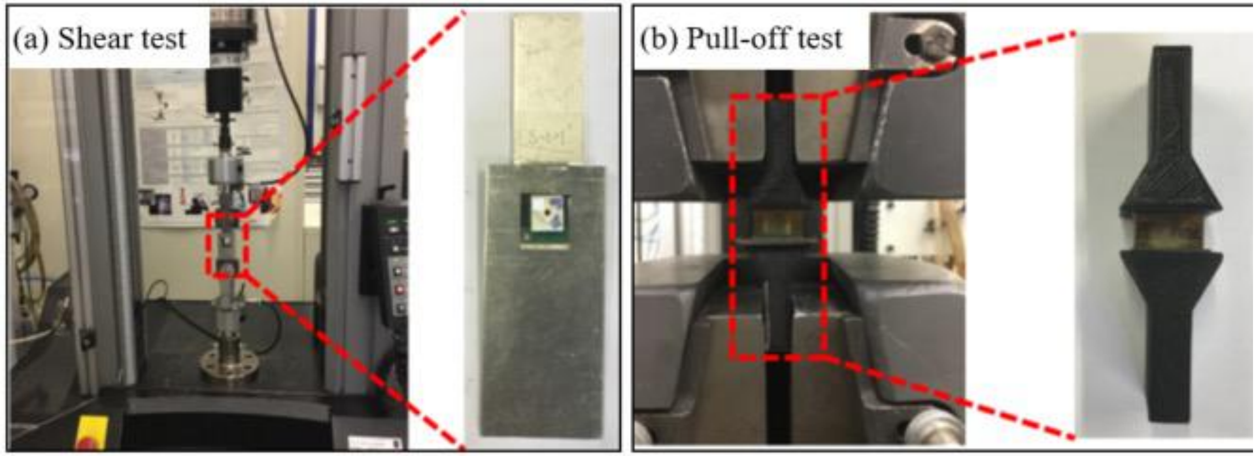


Dimensional change with temperature of 3 composite samples (Manufactured under the same conditions with the SEM samples)

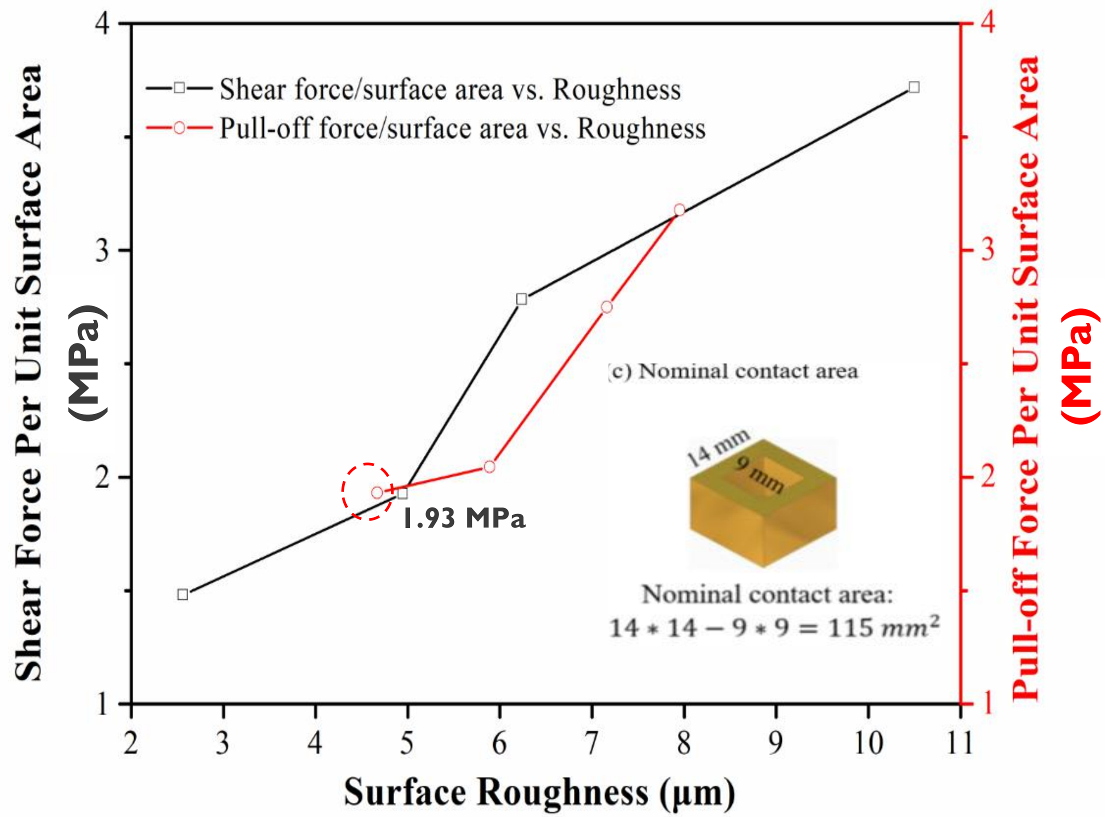
The results show that α_1 is close to the CTE of commercial PCB, indicating the part can bond well on the PCB when the IC runs at a temperature below 90°C.

Fei, Wei *et al.*, 2019 *SFF Symposium*

Adhesion properties measurements of resin-silica composite



Fei, Wei *et al.*, 2019 *SFF Symposium*

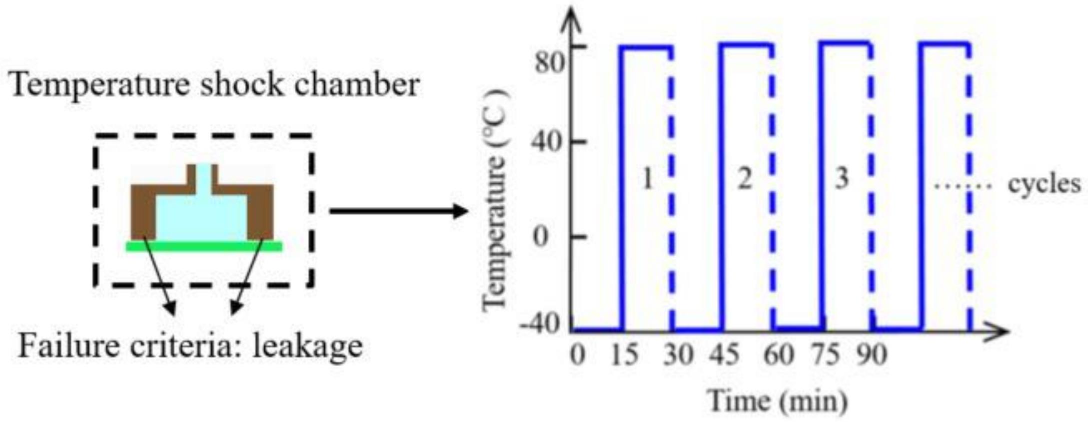


- Adhesion properties between different part/PCB substrate showed the adhesion on the part-PCB interface depends on their surface interactions.
- The larger the interface roughness, the greater the interaction forces on the contact surface.
- All the pull-off test and pressure test prove the bonding force between part-PCB is strong enough to keep them as an integrity system.

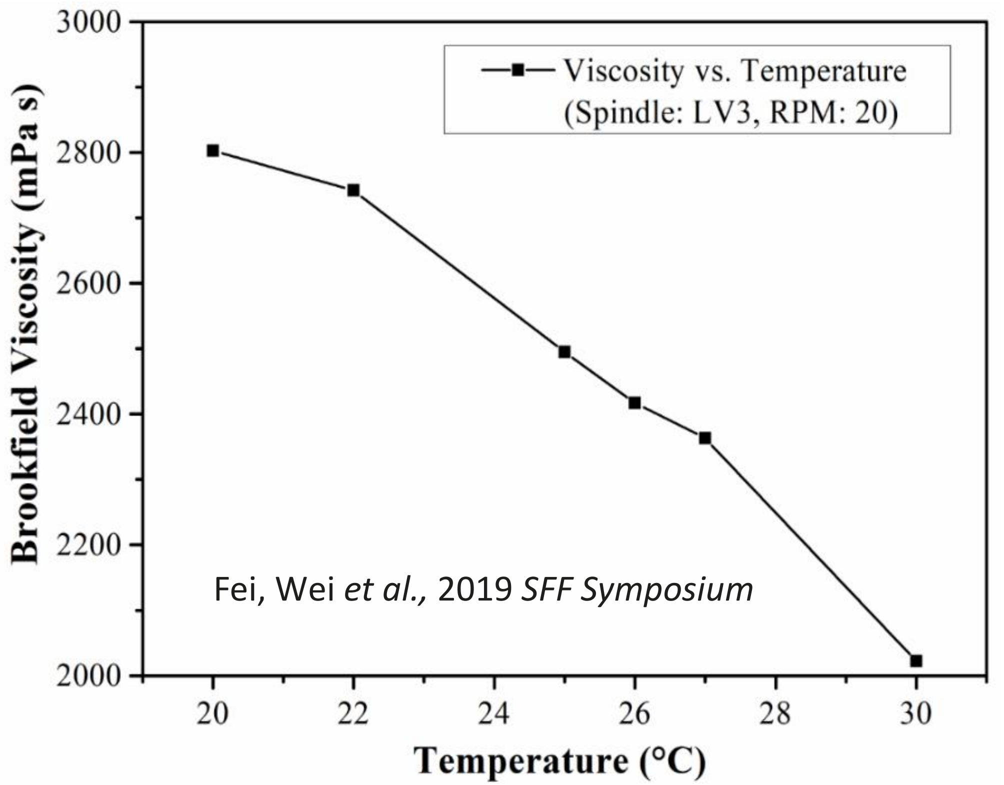
The influence of surface roughness on adhesion forces.

Suspension viscosity and particle dispersion of resin-silica composite

Fei, Wei *et al.*, 2019 *SFF Symposium*



The thermal shock test



Variation of the viscosity of silica-resin suspensions with temperature

- Regarding the printing material, the silica-resin suspension containing 60 vol.% silica is uniformly enough to ensure the flowability during printing, at the same time, it has a low CTE which is close to that of the PCB material.
- The thermal cycling test indicated the tailored part owned good CTE compatibility with the PCB substrate.

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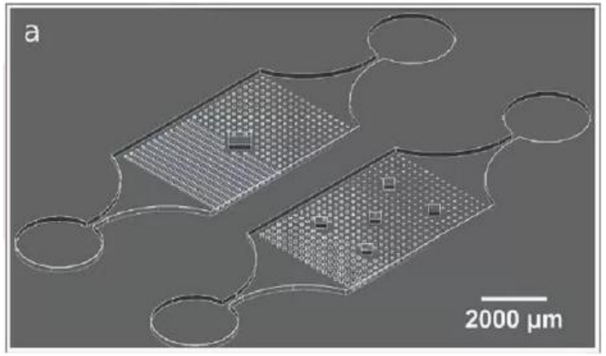
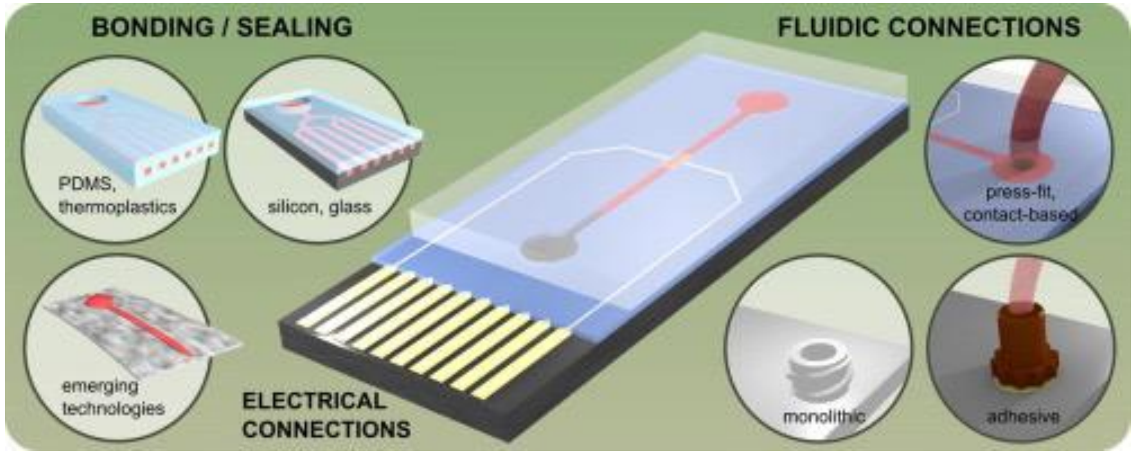
Alternative fabrication: Glass cooler

Fabrication of microstructures in glass

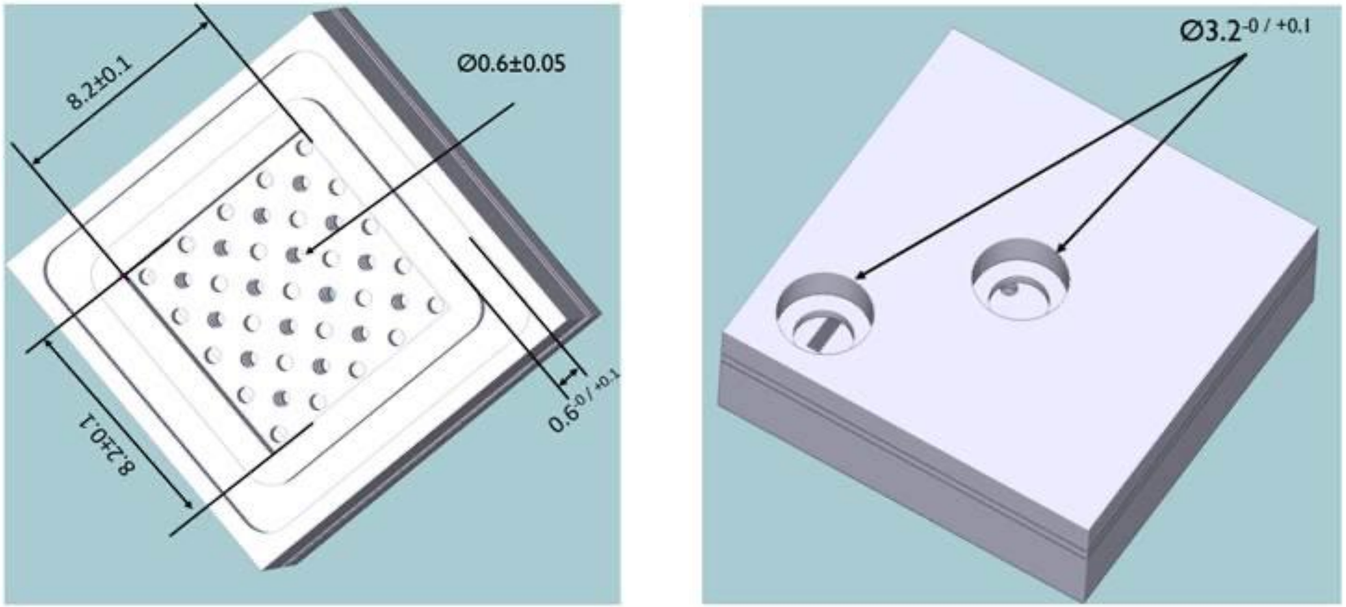




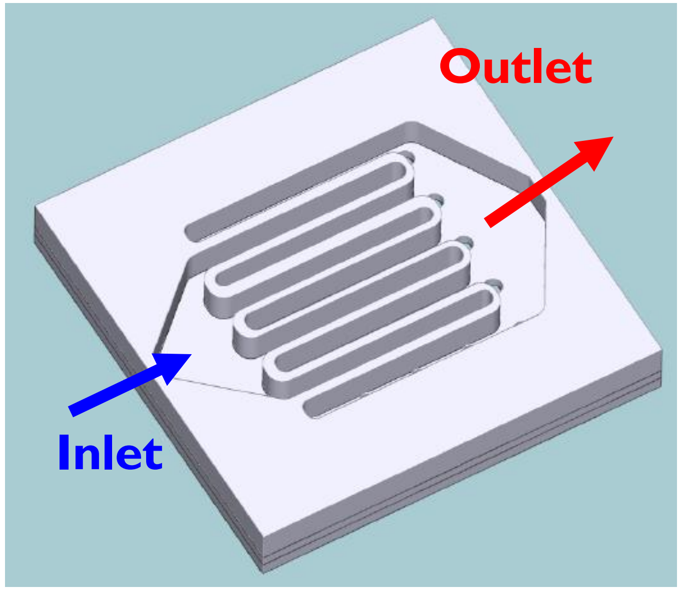
Yuksel Temiz, Robert D. Lovchik, Govind V. Kaigala, Emmanuel Delamarche, Lab-on-a-chip devices: How to close and plug the lab?, Microelectronic Engineering, Volume 132, 2015, Pages 156-175,

- Recent developments in glass fabrication enable internal microstructures
- Interesting material properties for our cooler (material: fused silica) :
  - CTE 0.5 ppm/°C → more compatible with Si and substrate than polymer
  - High temperature resistance
- Explore feasibility for glass cooler → adapt cooler design for glass microfabrication design rules

Design considerations: Glass cooler



Design 1



Design 2

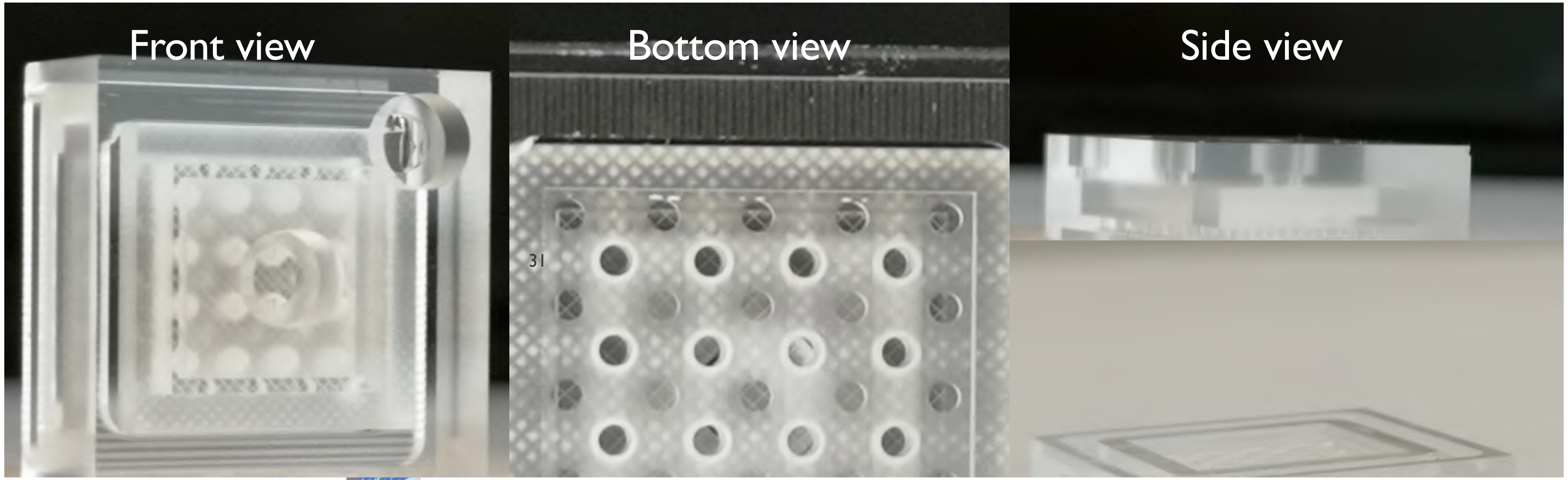
- 2 fabrication options:
  1. Monolithic structure
  2. Welding bonding
- Designs for both options finished
- Fabrication ongoing

Manufacturability

Resolution	< 1 µm
Surface roughness	Ra < 100na
Aspect ratio	> 1:500
Glass-to-glass seal withstands	100 bar

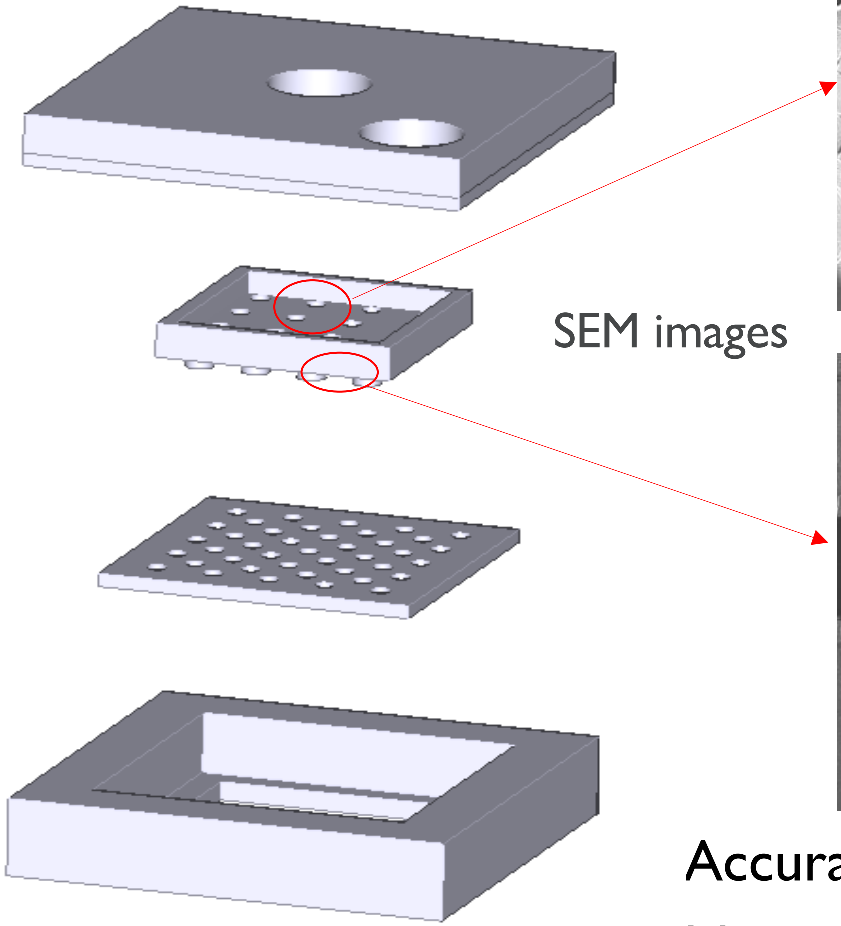
Demonstration of the Glass cooler

- Glass has interesting material properties:
  - Lower CTE than printed polymers → more compatible with Si and package
  - High temperature resistance
- Subtractive manufacturing technique used to create complex internal structures:
  - Focused laser beam locally modifies the density inside the glass
  - Cavities created by additional chemical etching
- Demonstrated for cooler geometry: 4x4 nozzle array design

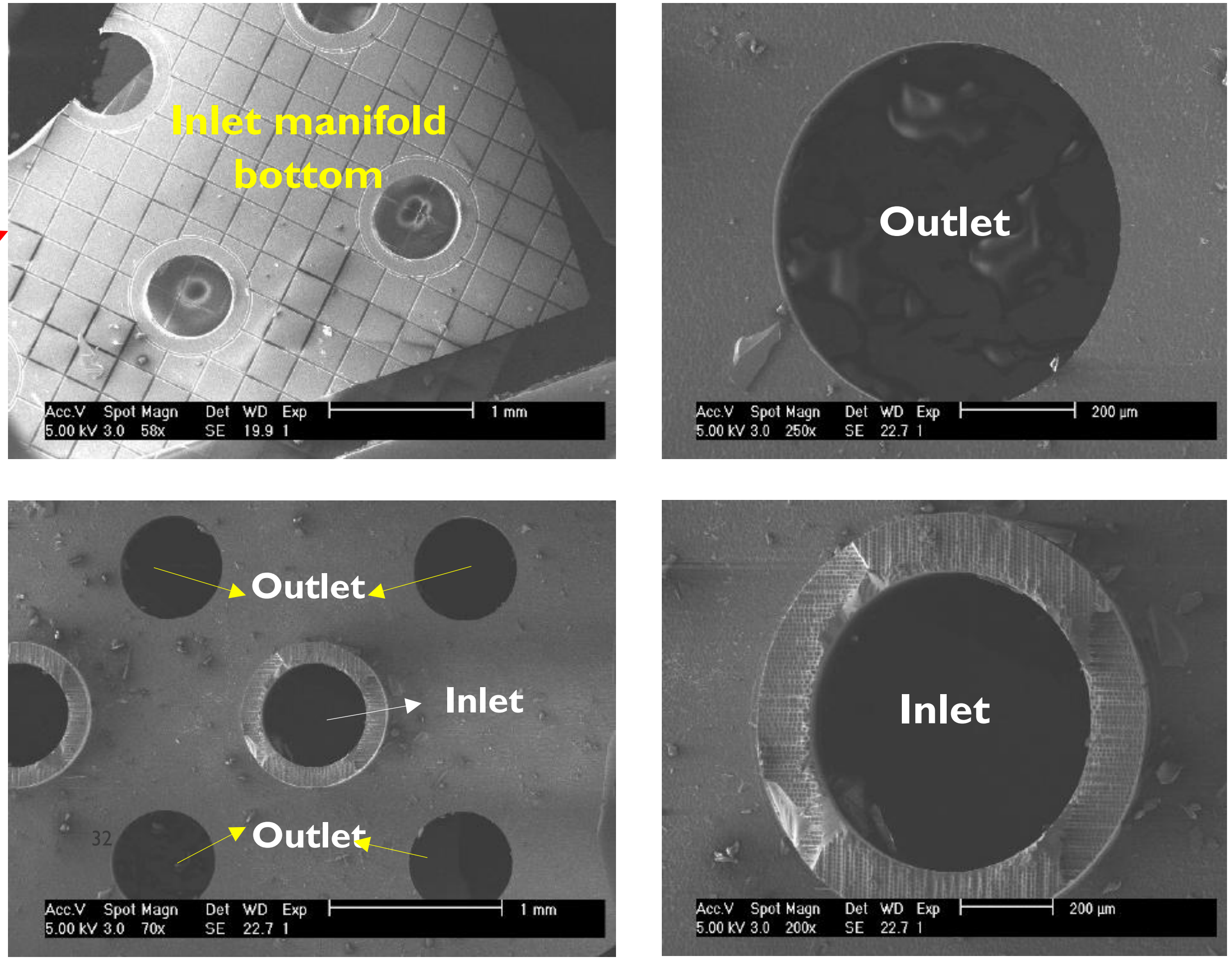


Demonstration of the Glass cooler

Wei, *Ph.D. thesis, 2020*



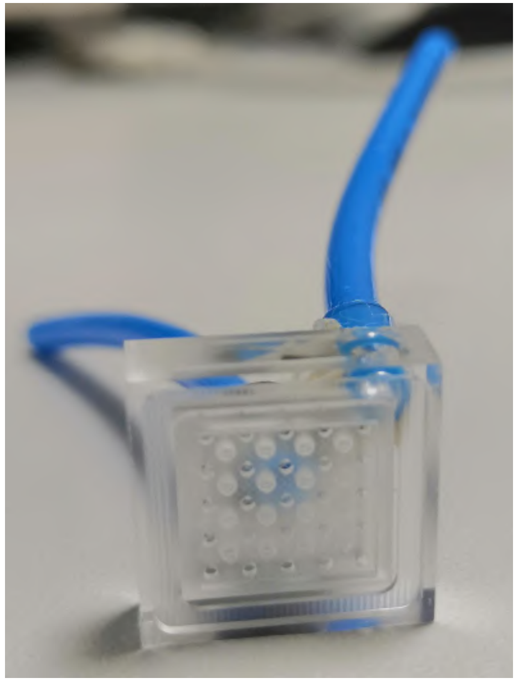
SEM images



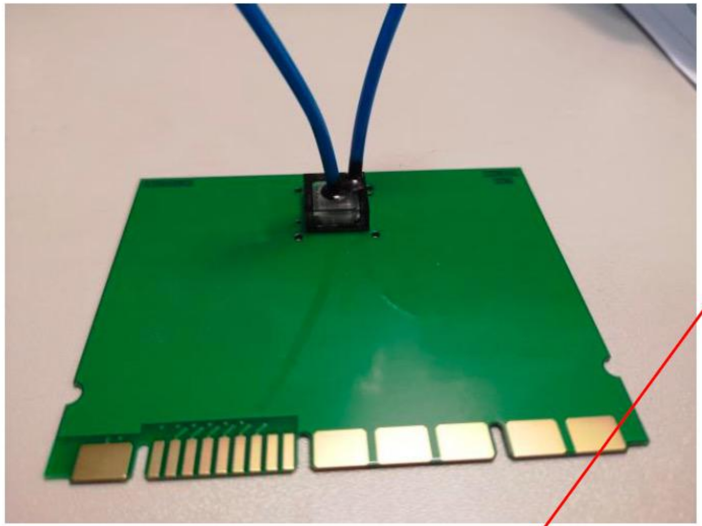
Accurate fabrication of internal geometry and circular nozzles

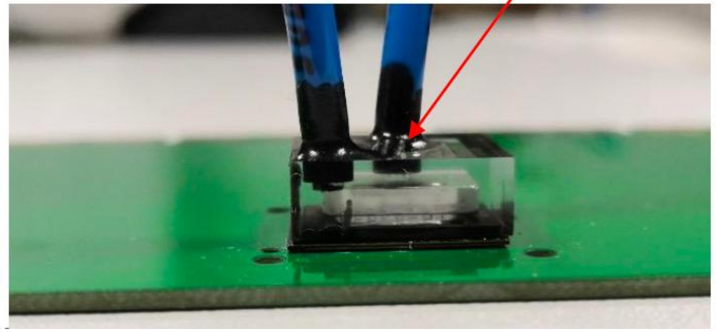
Measured nozzle diameter 605 ± 5 μm (nominal design 600 μm)

Assembly of the Glass cooler on to the packaging



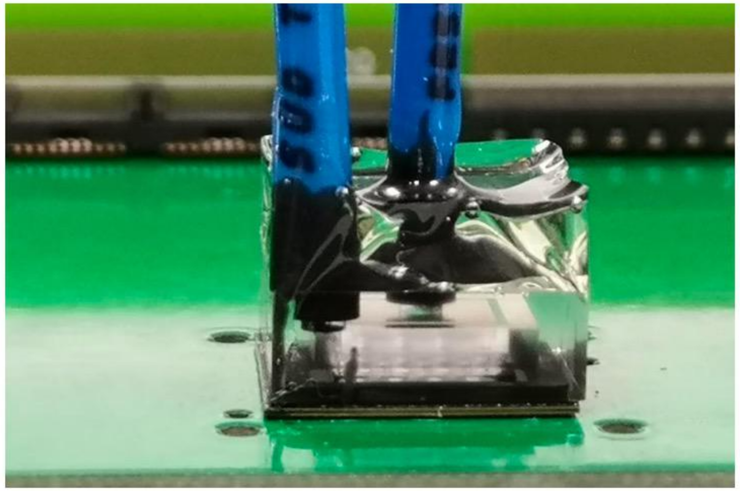
Wei, *Ph.D. thesis, 2020*





PTCQPLUS soldered to PCB
Glass cooler glued to the package
In-/Out-let tubes glued to the glass cooler

Water leakage at the in-let tube connection point



Additional epoxy applied to strengthen tube connections

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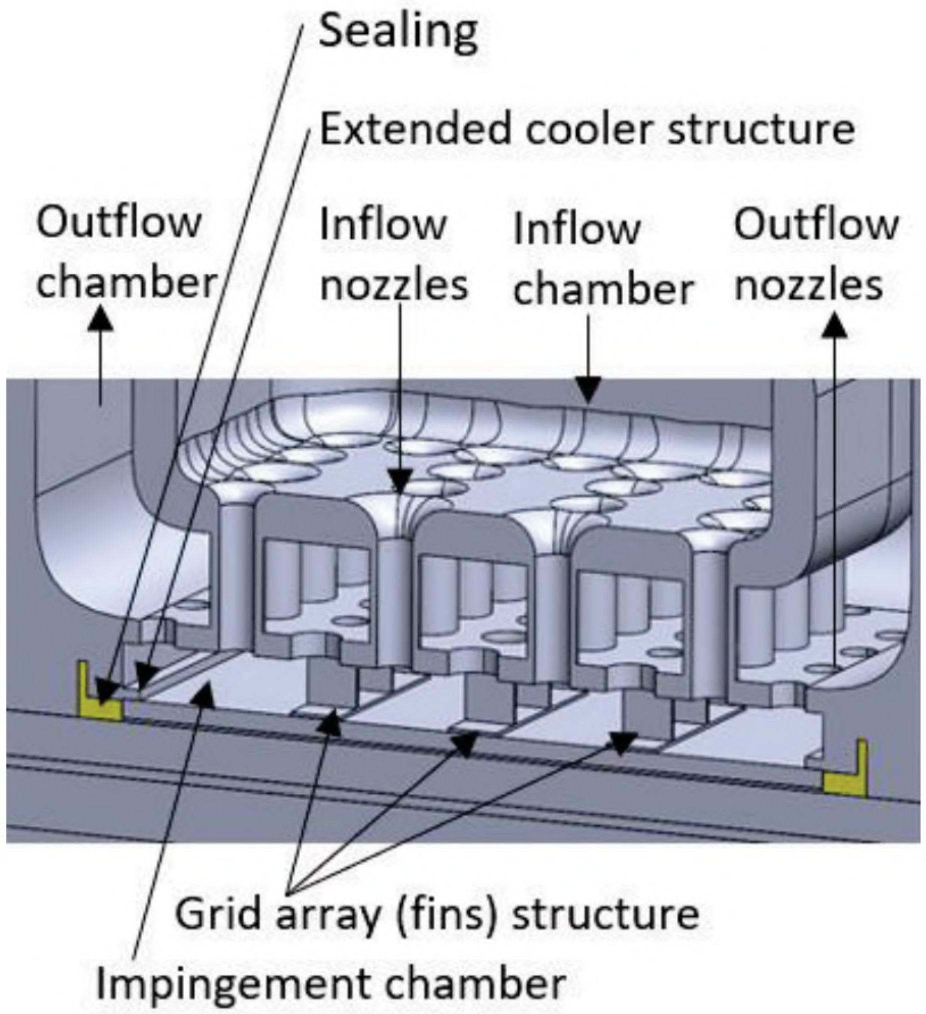
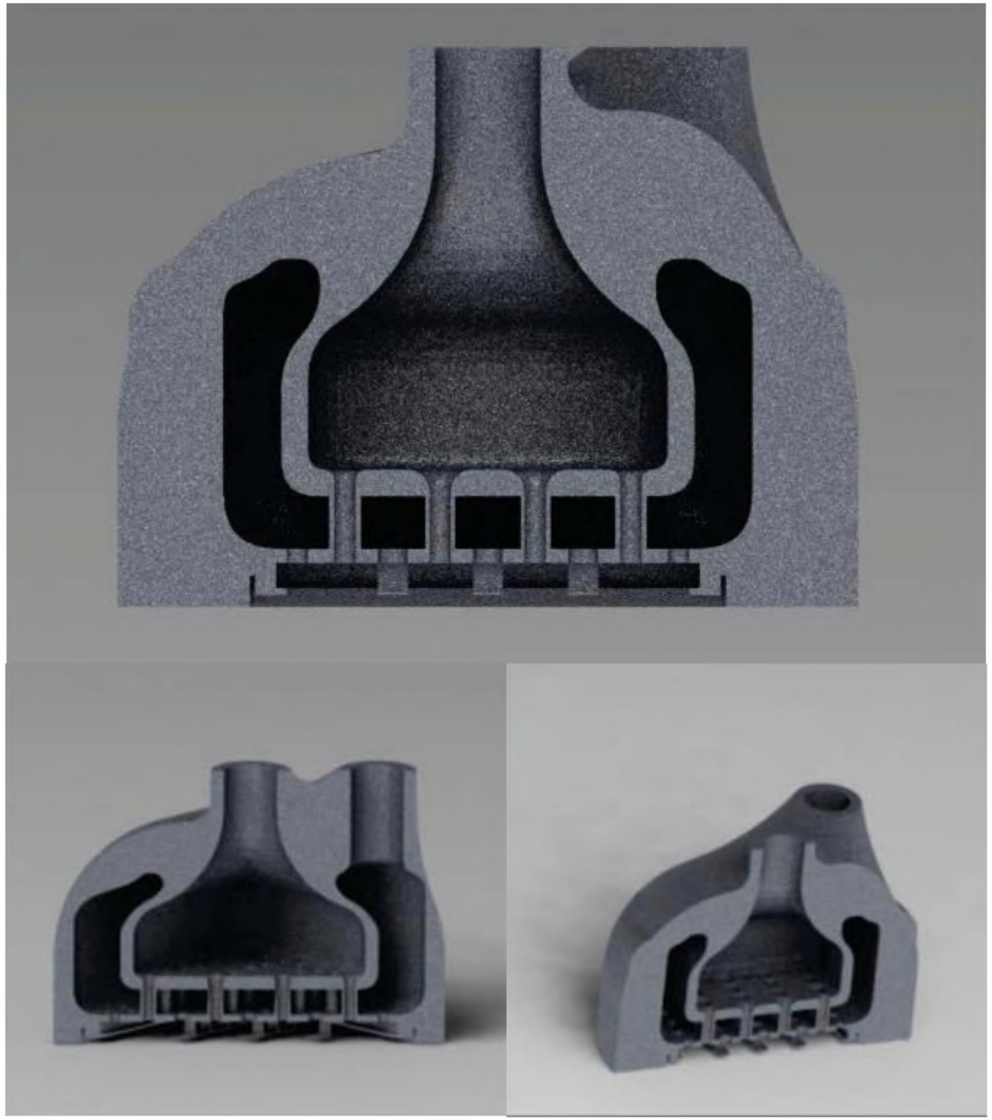
Metal 3D-Printed Direct Liquid Jet-Impingement Cooling

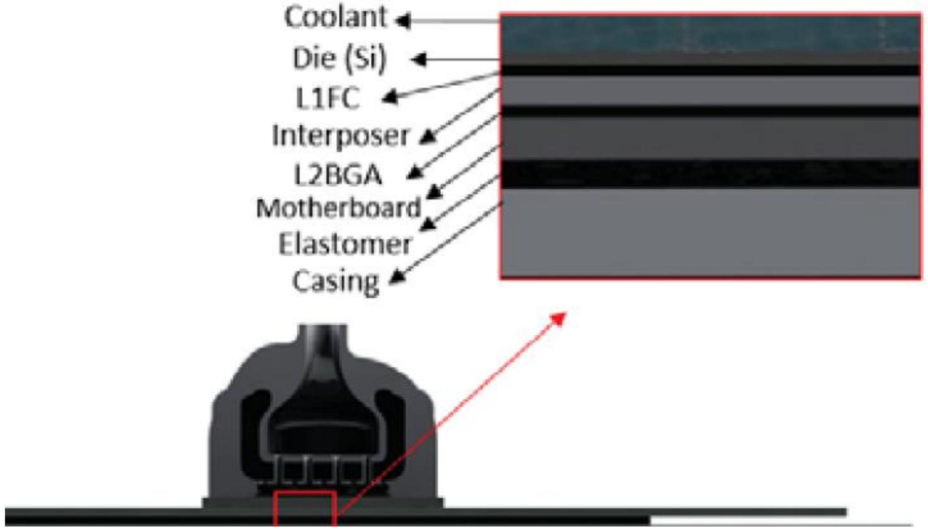
- The advantages of metal 3D printing are numerous, such as the improved dimensional stability and the minimum warpage and shrinkage of parts.
- For the specific application it can be mentioned also the reduction of the CTE mismatch between metal cooler and PCB, on the integration and reliability point of view and the not absorption of liquid by the device.
- More in general, 3D printing makes possible to manufacture parts with shapes and geometries that no other techniques can.

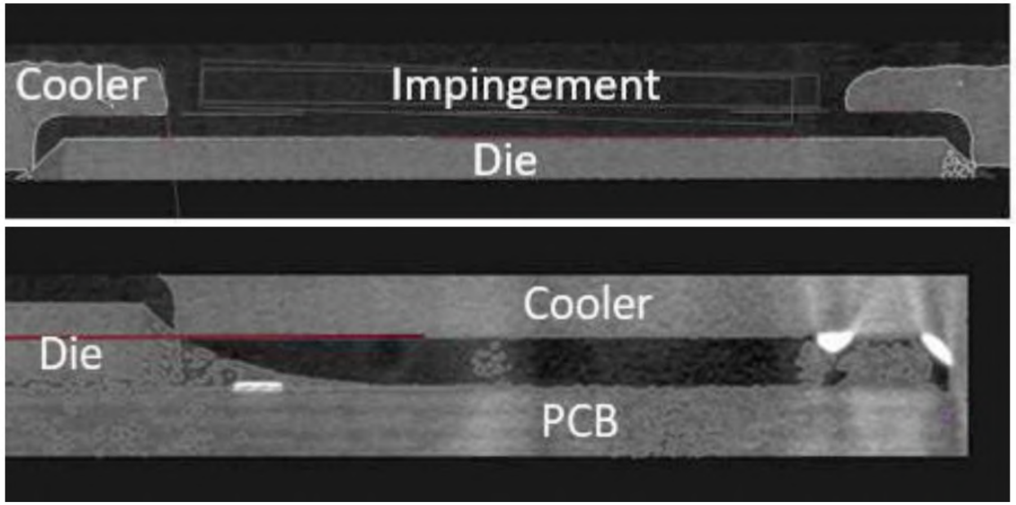


Pappaterra, Antonio, et al. "Advanced (Metal 3D-Printed) Direct Liquid Jet-Impingement Cooling Solution for Autonomous Driving High-Performance Vehicle Computer (HPVC)." EuroSimE. IEEE, 2021

Metal 3D-Printed Direct Liquid Jet-Impingement Cooling

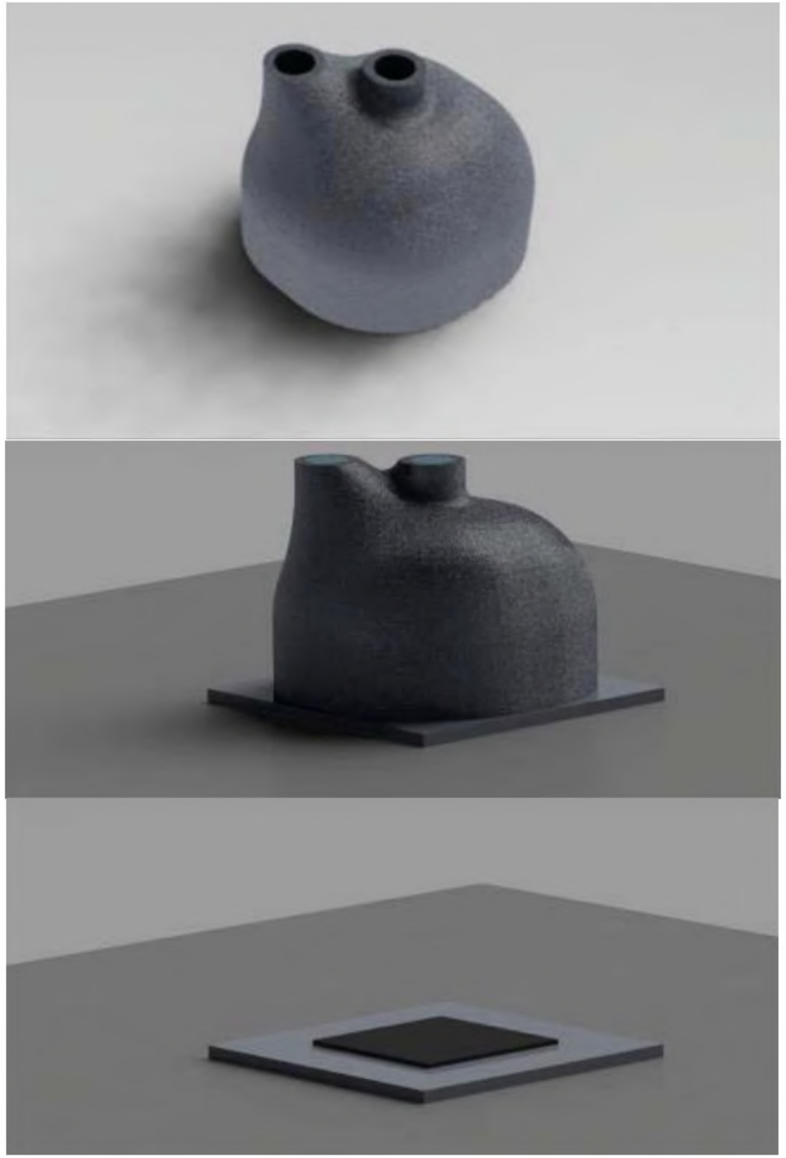


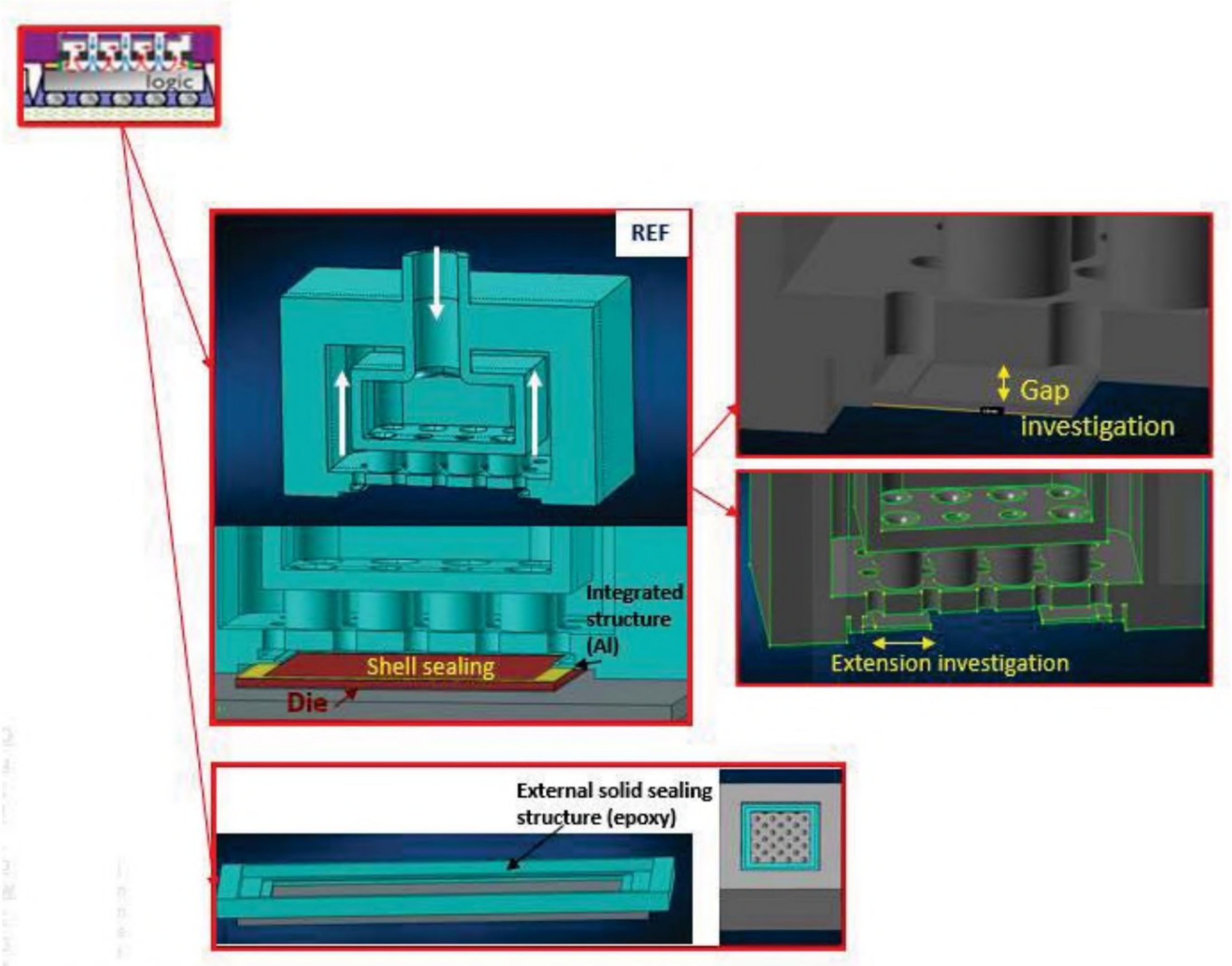




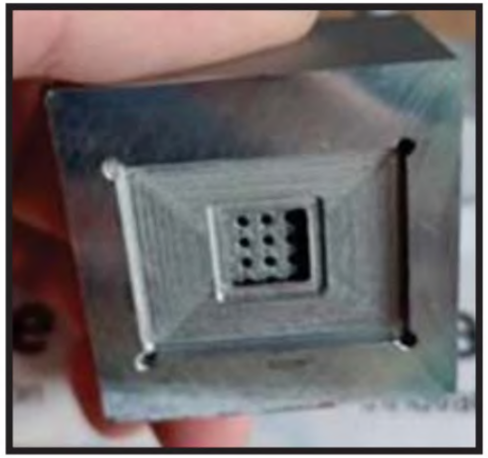
CTS from the side of the cooler

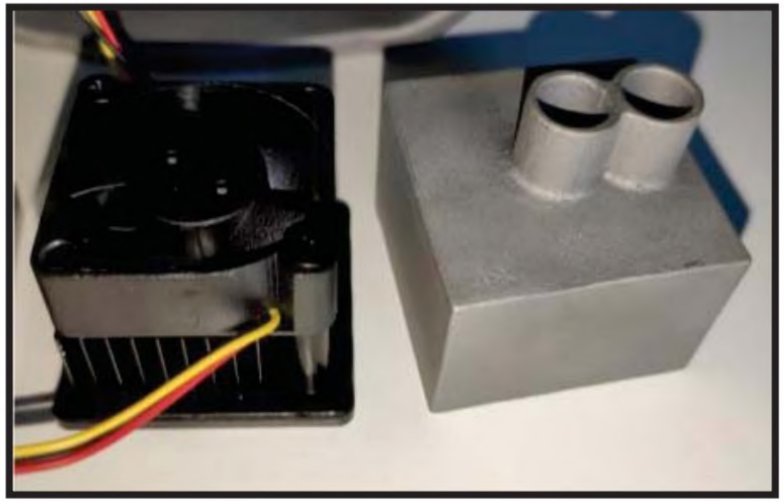
Metal 3D-Printed Direct Liquid Jet-Impingement Cooling

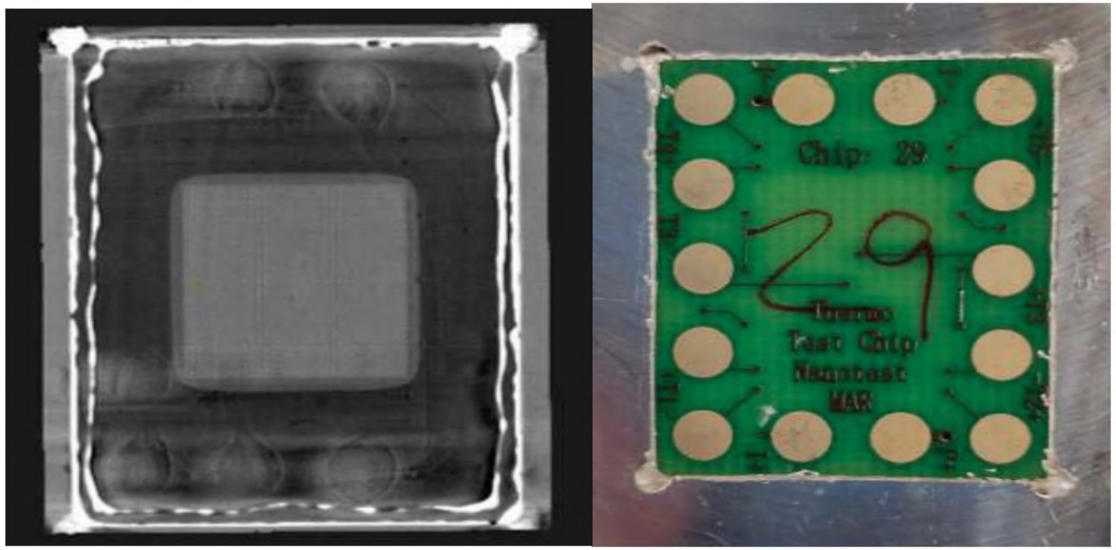




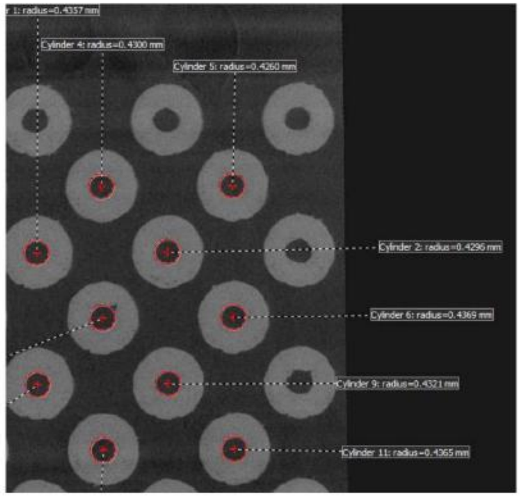
Metal 3D-Printed Direct Liquid Jet-Impingement Cooling







Computed tomography scan (CTS) from the top and picture from the bottom of the chip bonded to the cooler



CTS nozzles diameters

Computed tomography scan (CTS) from the top and picture from the bottom of the chip bonded to the cooler

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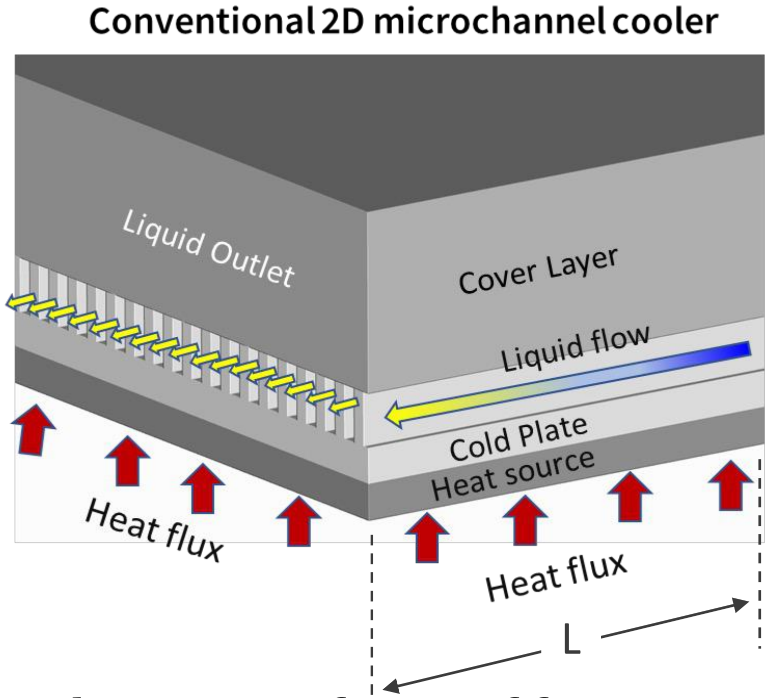
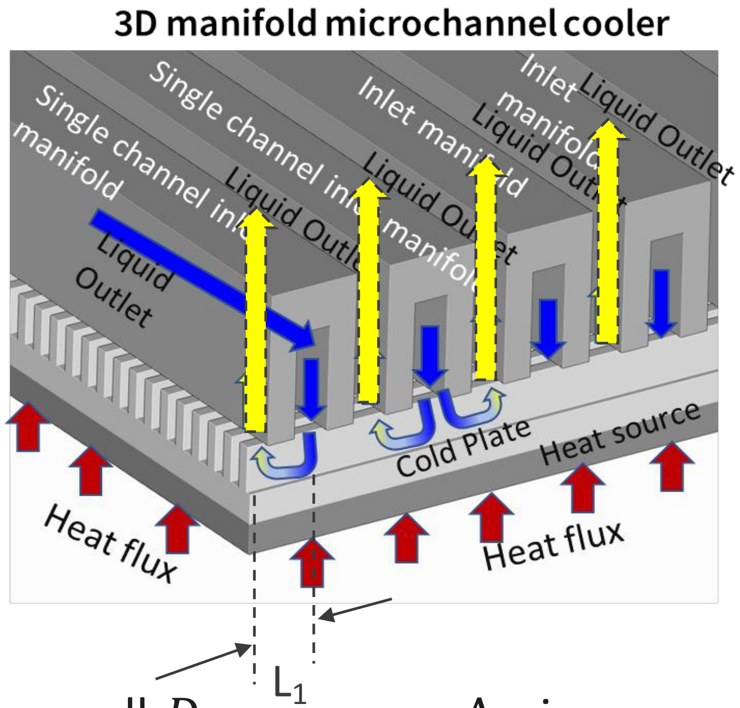
Embedded microchannel with 3D manifold

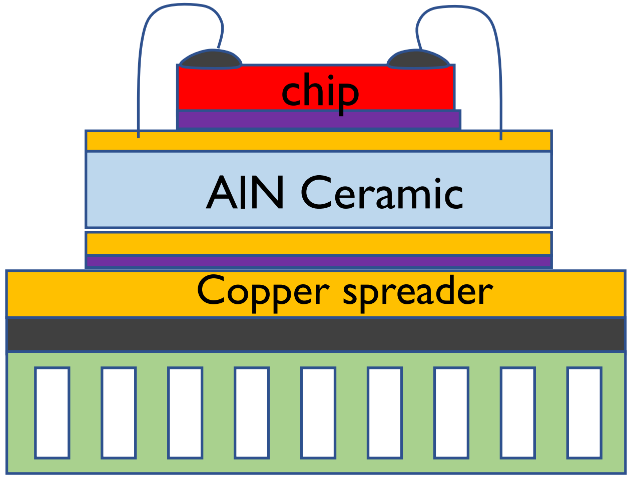




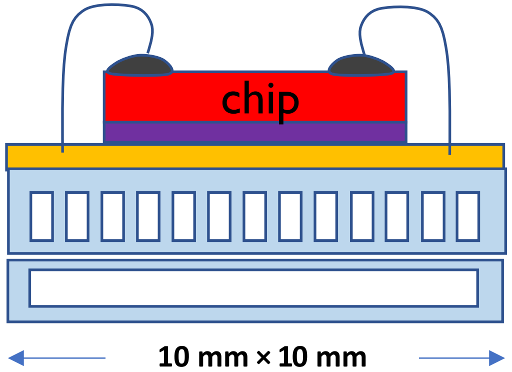
- Higher $heat\ transfer\ coefficient$ requires small D_h, however, Δp increases → system pump power ↑
- To reduce Δp , decreasing L using **3D manifold** to deliver cold liquid from the top and collect the hot fluid using U-shape "short" micro-channel
- This results in smaller pressure drop, temperature uniformity, higher heat transfer coefficient, and higher heat flux > 1kW/cm^2

Embedded microchannel cooling for power electronics

Fluidic Cooling	Cold-plate	Ceramic substrate	Chip
	Conventional package with cold plate cooling	Compact package with DBC embedded u-channel cooling	Ultra-compact package with chip embedded u-channel cooling



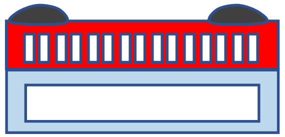
Heat Sink



Ceramic

2D manifold

3D manifold

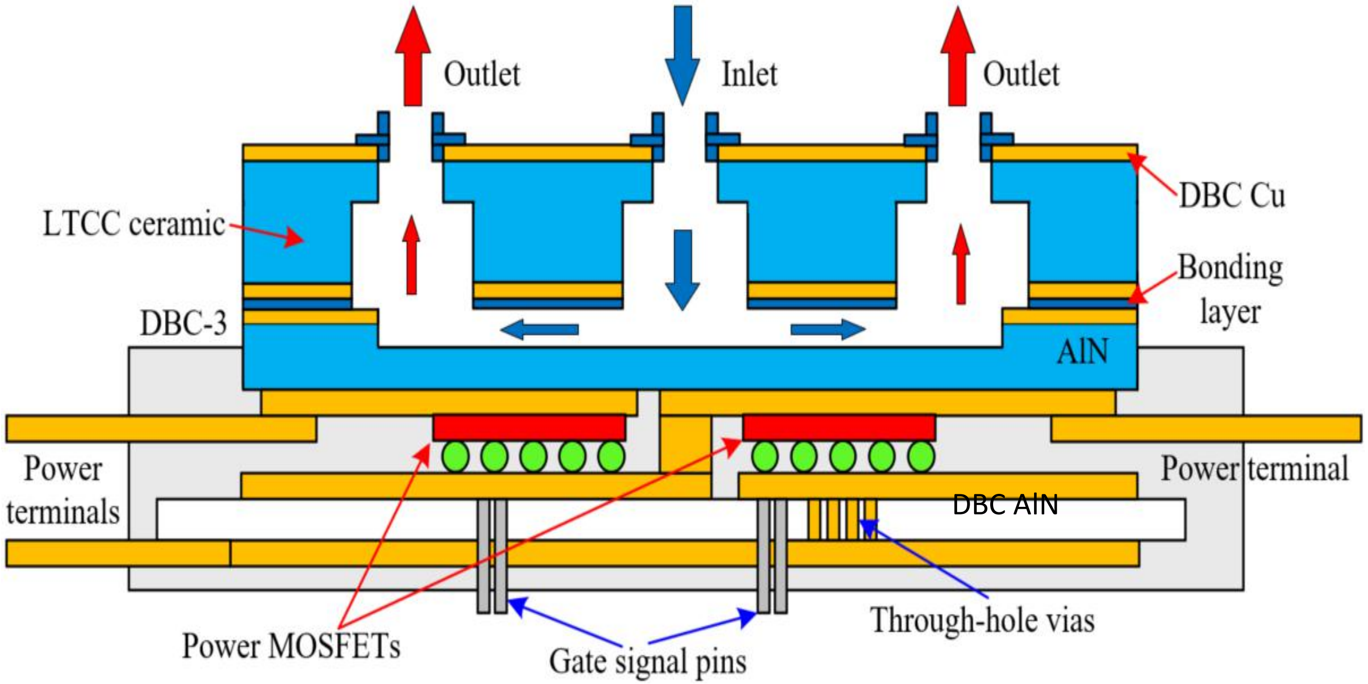

chip

3D manifold

- Power electronics packaging is different → high electrical voltage
- Embedded u-channel inside device needs dielectric liquid
- Ceramic-based channel cooling is promising!

Package-level ceramic-based microchannel cooling integration for power electronics

POETS project: Heterogeneous SiC Power Modules with DBC Active (laser cut) Microchannel Cooling



- Embedded micro-channels into aluminum nitride substrate
- Heterogenous integration: micro-bump bonding and through hole vias
- Electrical-thermal co-design
- Single side cooling → future double side cooling

STANFORD nanoHeat

Ford

PURDUE UNIVERSITY

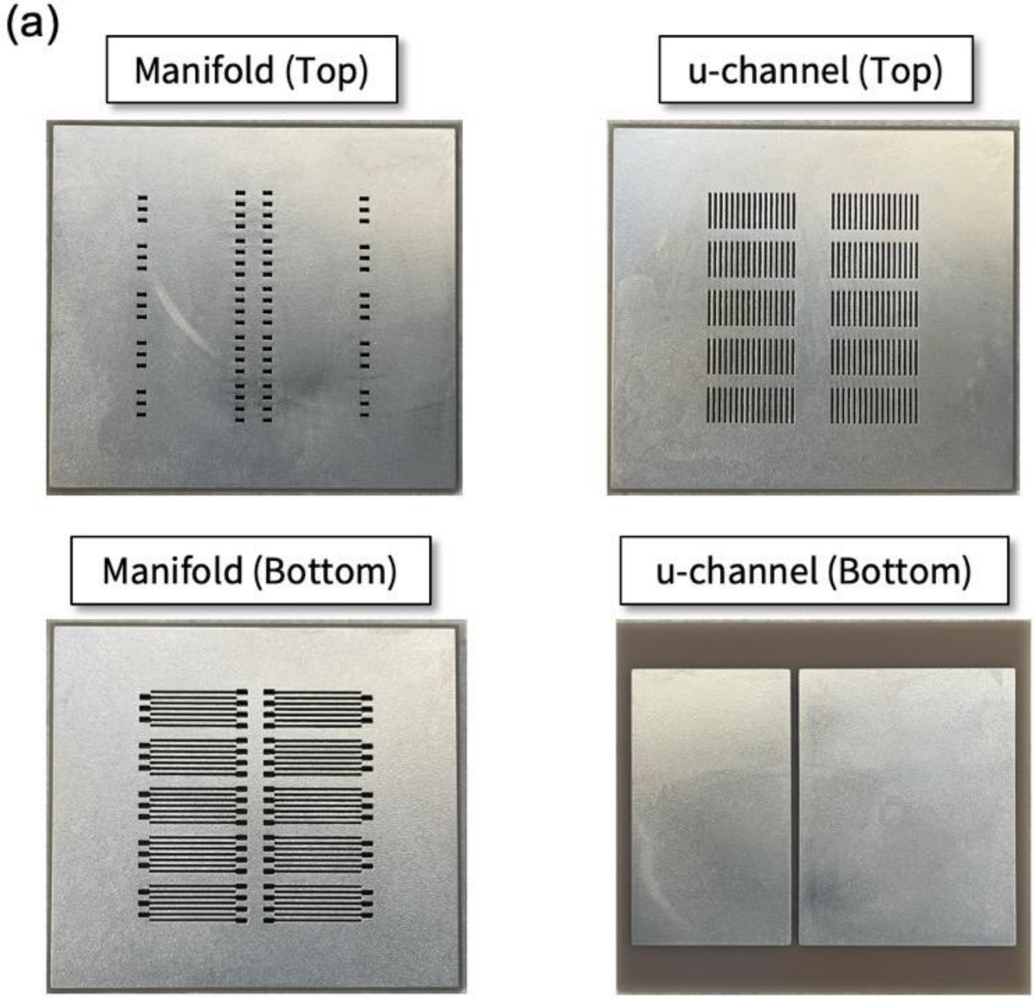
Semiconductor Packaging Laboratory

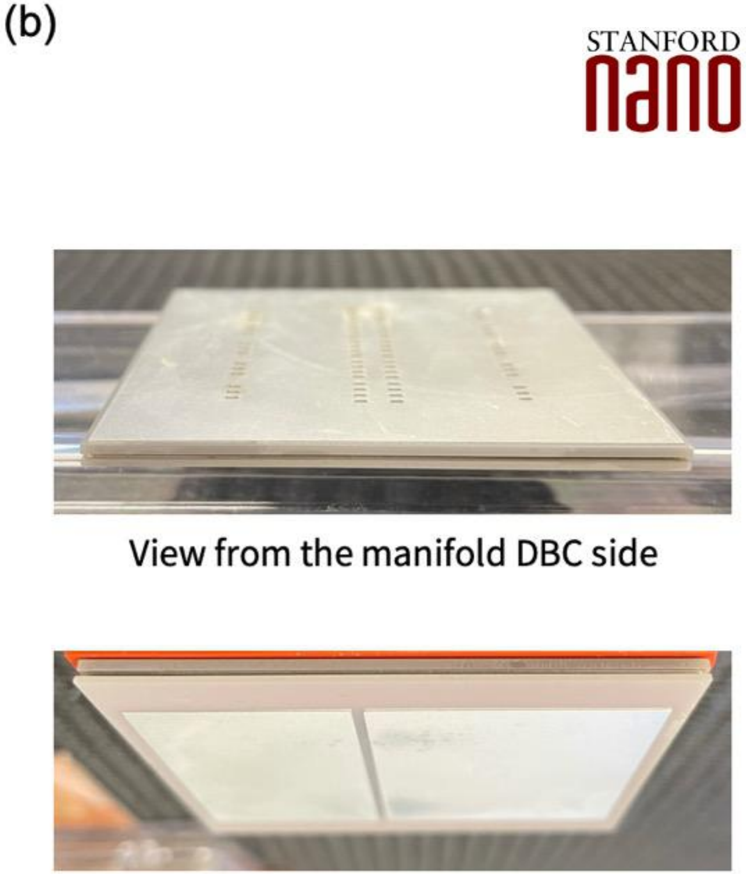
(All-in-one for Semiconductor Packaging, Heat transfer, and Assembly Lab)

S-PACK Lab

(Advanced Packaging)

Package-level ceramic-based microchannel cooling integration for power electronics





View from the manifold DBC side

View from the u-channel DBC side

STANFORD nanoHeat

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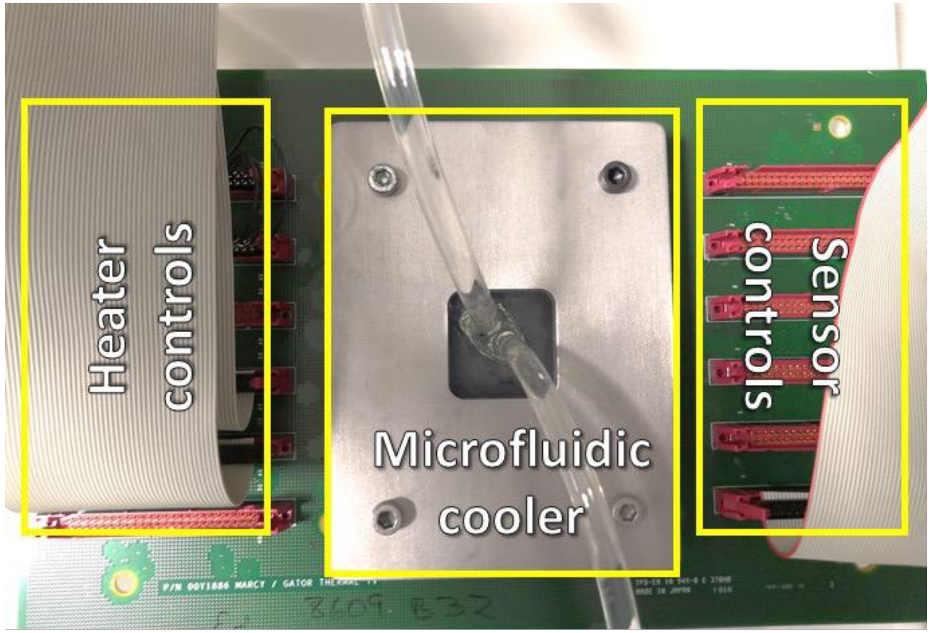
Long term thermal measurement

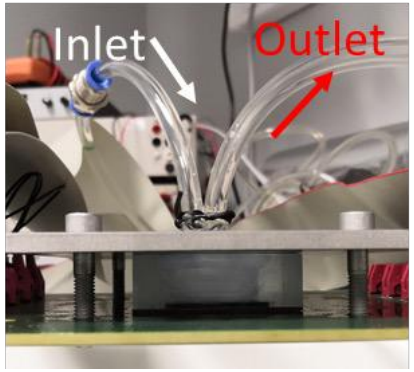
INTRODUCTION

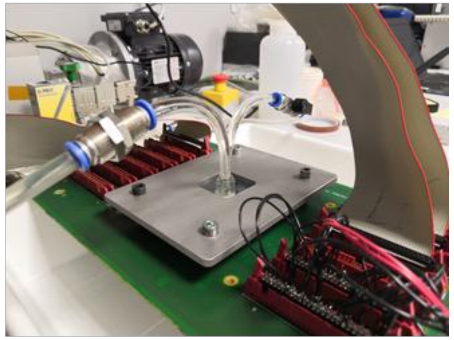
- Objective: long term measurement of the μcooler
  - Most challenging case: bar die package
  - Identify reliability issues

PROCEDURE

- Duration: 1000h
- Monitor chip temperature .....
  - Measure every day (24 hours)
- Evaluate cooler geometry:
  - Optical inspection with microscope
  - Measurement at beginning and end of test



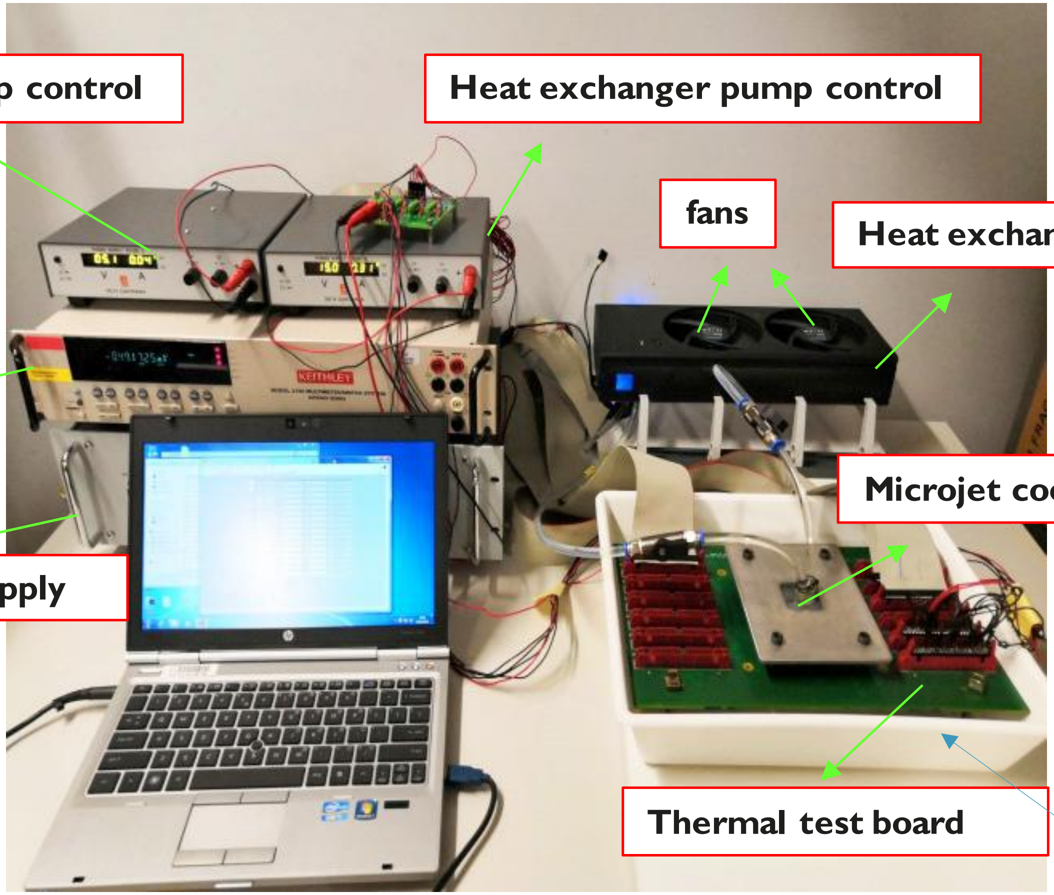




Test chip and test board
Courtesy of Global Foundries

Long term thermal measurement

MEASUREMENT SET-UP

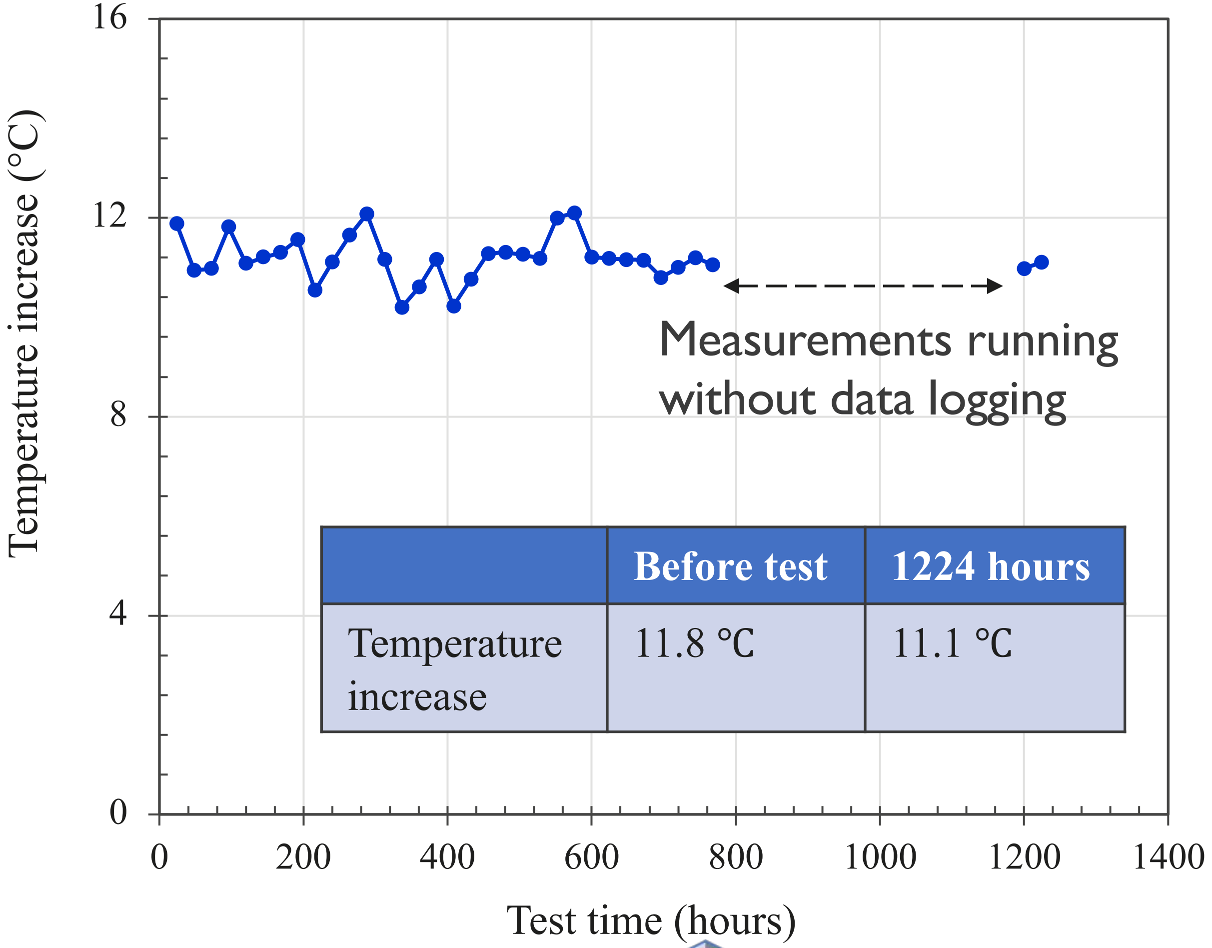


- Simplified set-up developed for thermal and flow measurement
- Integrated pump and heat exchanger for coolant flow loop
  - Fan control
  - Pump control
  - No flow rate control and measurement, can be estimated
- DI water used as liquid coolant
- No filters used in simplified test
- Temperature measurement in all 25 sensors of test chip
- Test board placed in plastic tray to check for leakage

Long term thermal measurement

RESULTS

Average test chip temperature increase above ambient



	Before test	1224 hours
Temperature increase	11.8 °C	11.1 °C

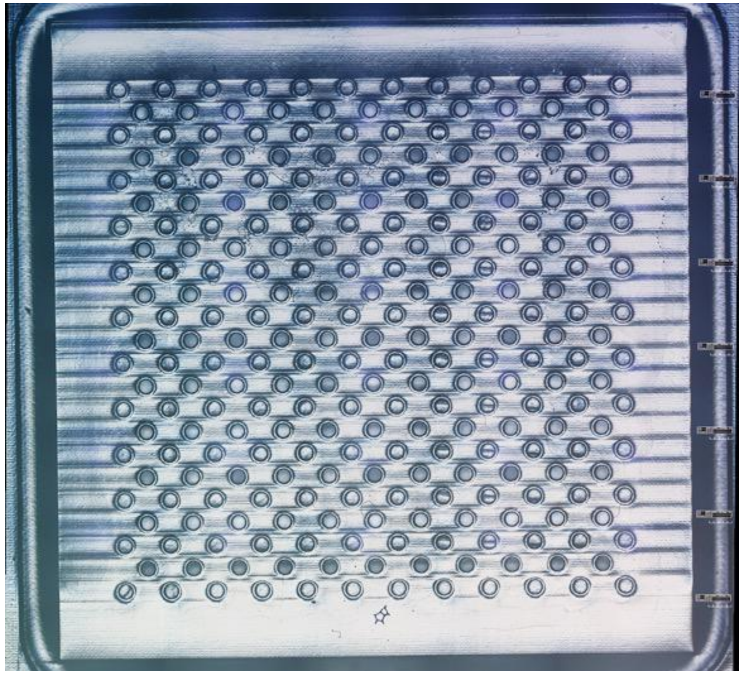
- Test conditions:.
  - Chip power: 30V / 90W
  - Pump voltage: 12V
  - Heat exchanger voltage: 10V
  - Flow rate at 12V: estimation 1.5 L/min
- Cooler performance and room temperature monitored for 50 days

Observations:

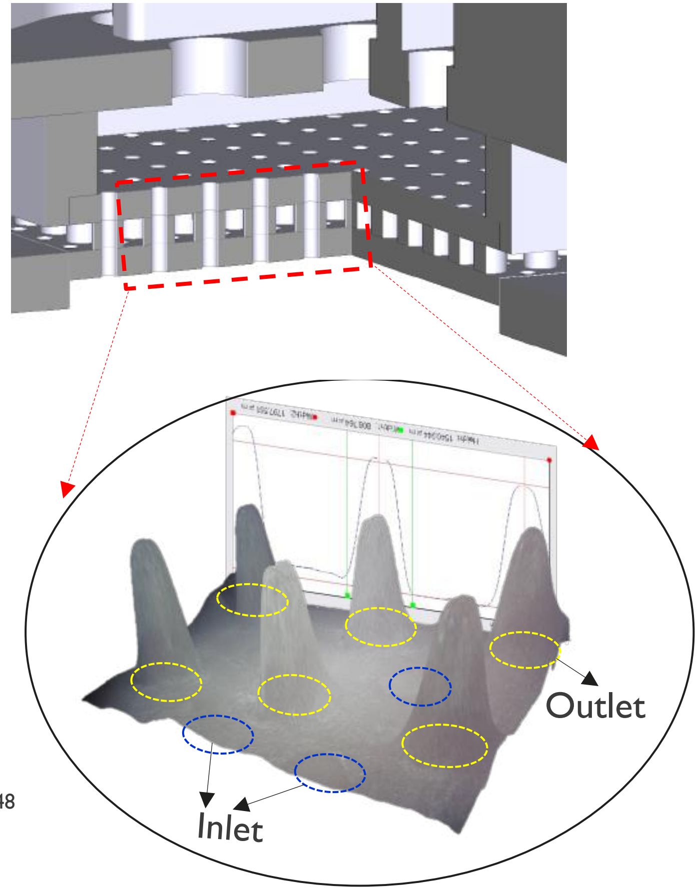
- No leakage observed during the test on the bare die package
- Consistent thermal performance during the 50 days → small variation
- Similar behaviour for all 25 sensors

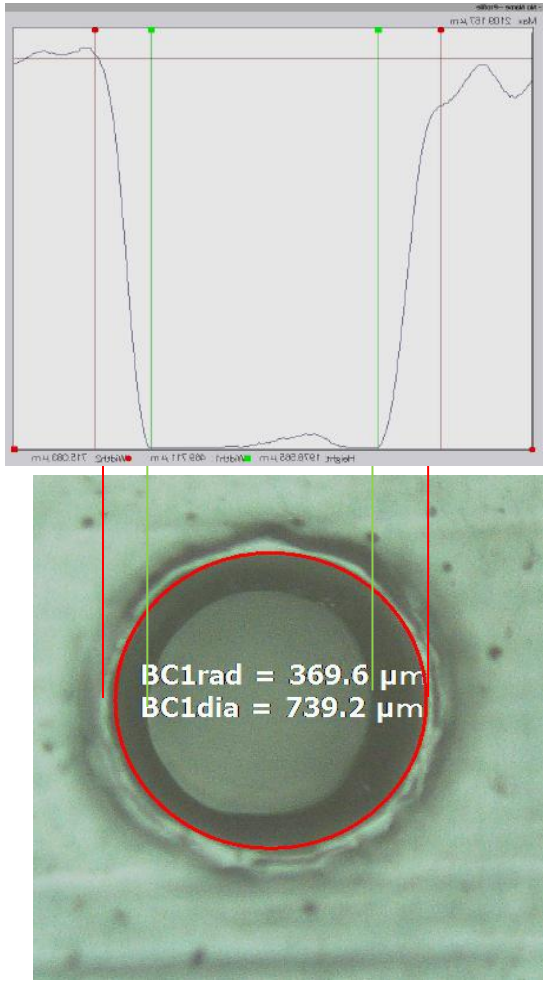
Long term thermal measurement

- Impact on cooler geometry: nozzle diameter



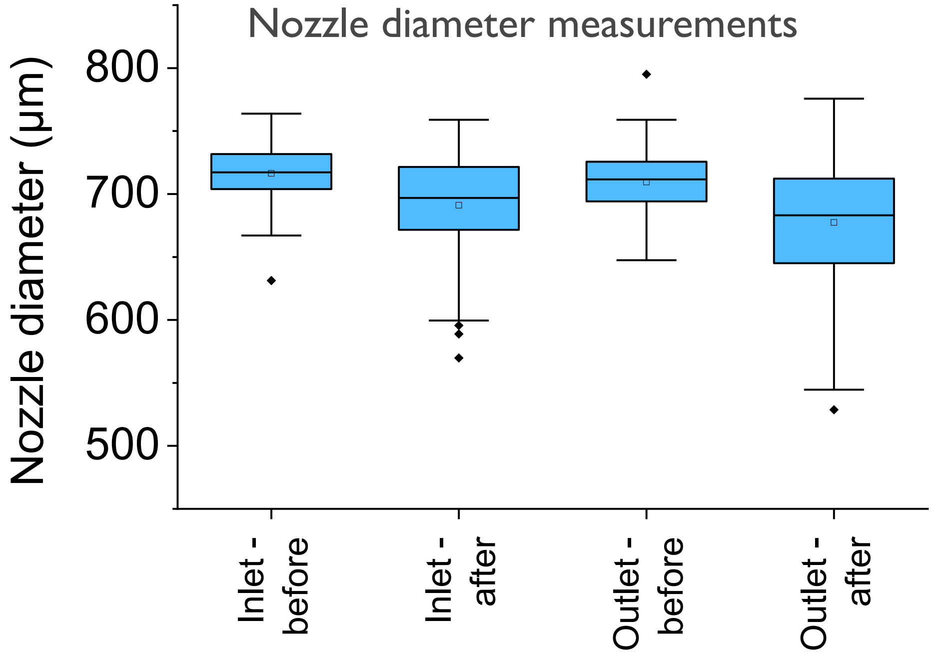
Bottom view
(11 x 11 inlet nozzle array)

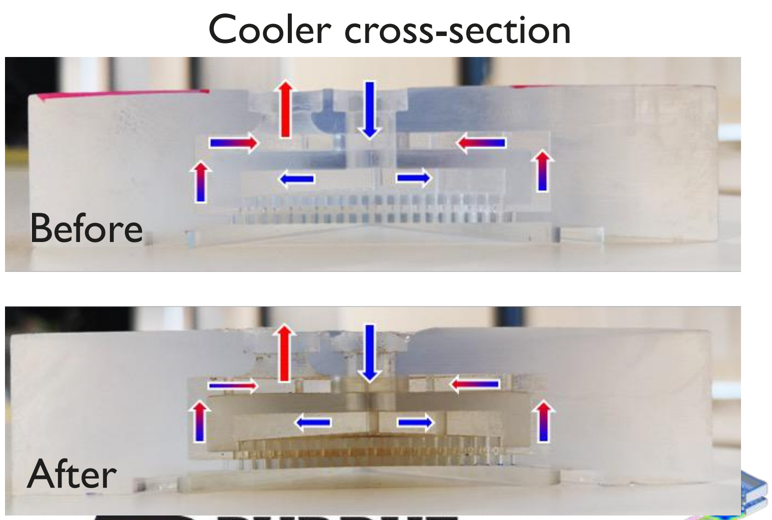


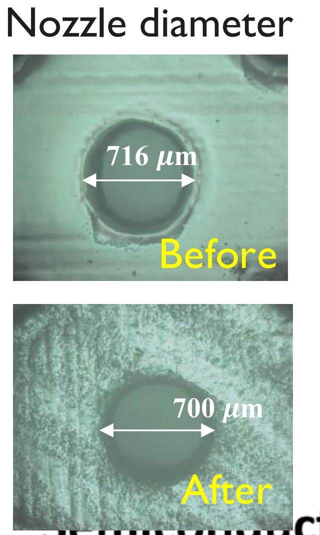


- Nozzle geometry and nozzle diameter evaluation with 2D and reconstructed 3D microscope image before the long-term measurement

Long term thermal measurement: impact of cooler nozzles





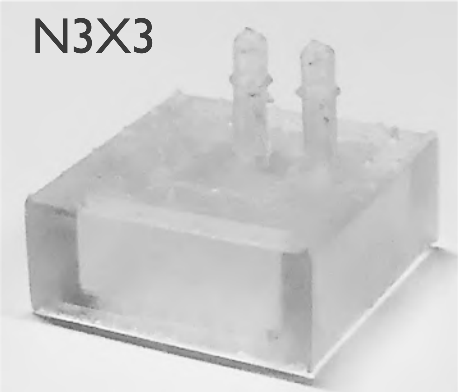


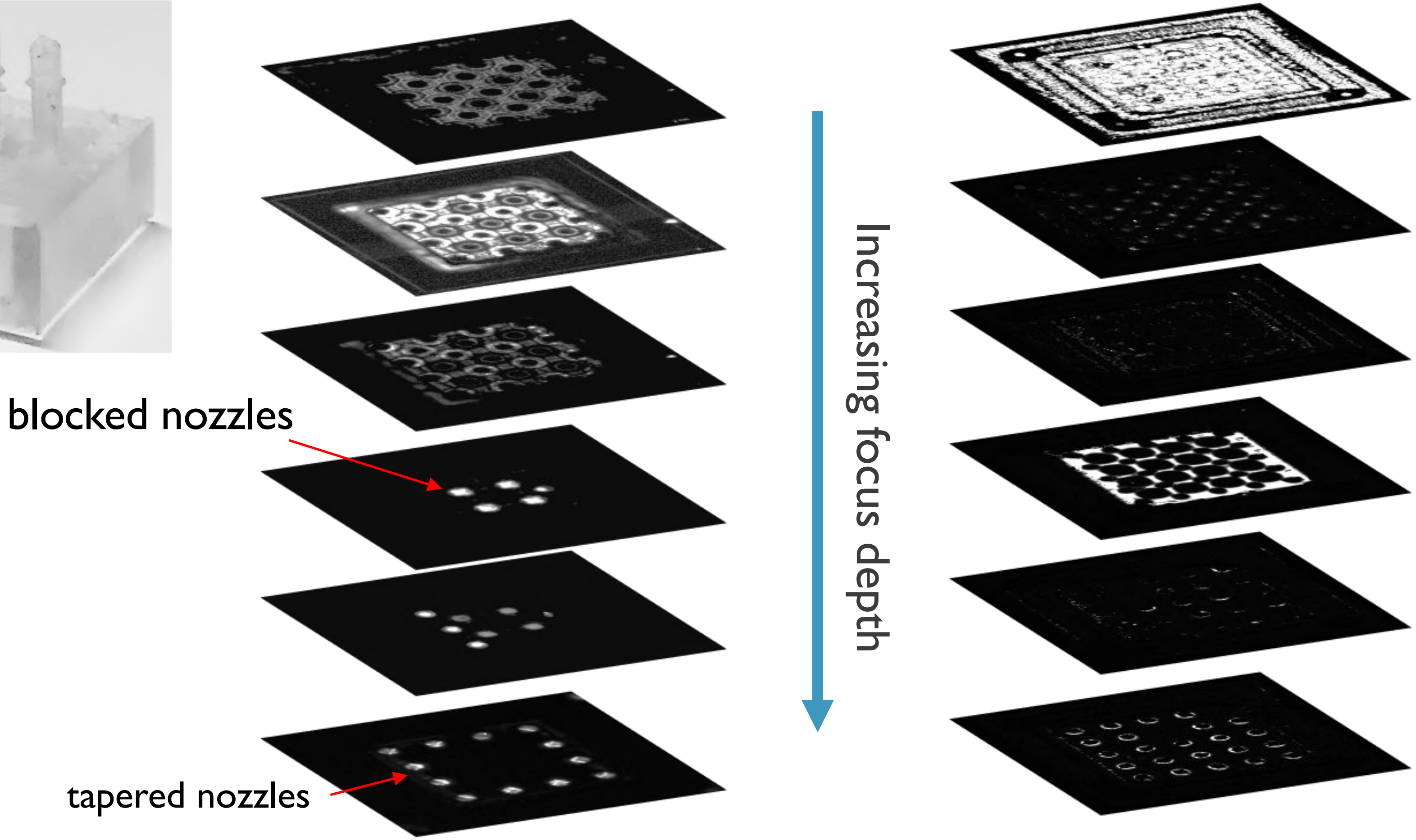
Observations after long term measurement with DI water for the 3D printed plastic cooler:

- ***No clogging*** of the nozzles or internal channels despite lack of filters in simple test setup
- No erosion of the nozzles.
- No significant difference for the nozzle diameters before and after the measurements
- Discoloration of the cooler material in contact with the cooler

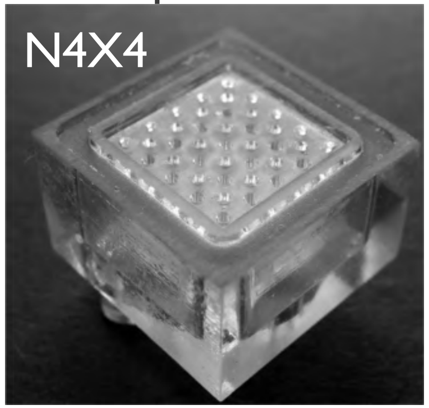
Defect measurements of 3d printed cooler

Gen-1 printed cooler





Gen-2 printed cooler



SAM image with blocked nozzles

SAM image with good nozzles

PURDUE UNIVERSITY

Semiconductor Packaging Laboratory

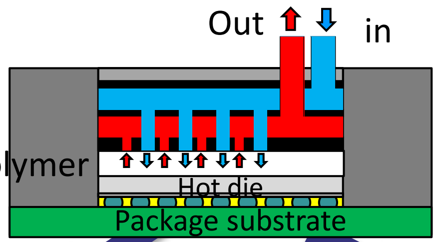
(All-in-one for Semiconductor Packaging, Heat transfer, and Assembly Lab)

S-PACK Lab

(Advanced Packaging)

Previous work: bare die impingement in package

Manufacturing strategies



Integrated the polymer-based jet cooler into the package

Cooler assembly with fixture

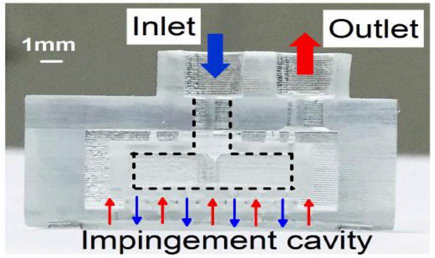
Proof of concept and fundamental study

Direct on substrate

CTE matched with the organic substrate

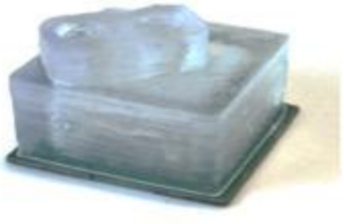
Micromachining cooler
(4X4 jet array nozzle diameter: ~500 μm)

Wei *et al., IEEE IEDM*, 2017



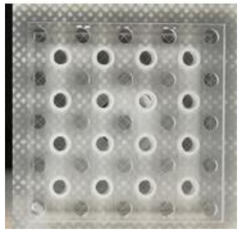
3D printing polymer cooler
(8x8 array nozzle diameter: 300 μm)

Wei *et al., IEEE ECTC*, 2018



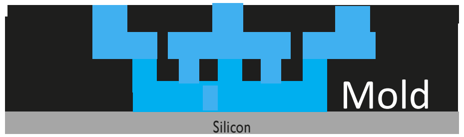
On-substrate direct printing cooler

Fei, Wei *et al.,* 2019 *SFF Symposium*



Glass cooler with low CTE

Wei, *Ph.D. thesis, 2020*



Cooler using injection molding and 3D printing sacrificial structure

Patented (Eric Beyne, imec)

THANK YOU FOR YOUR ATTENTION!