Fluid & Thermal Analysis of a Manifold Microchannel Heat Sink

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Presented By
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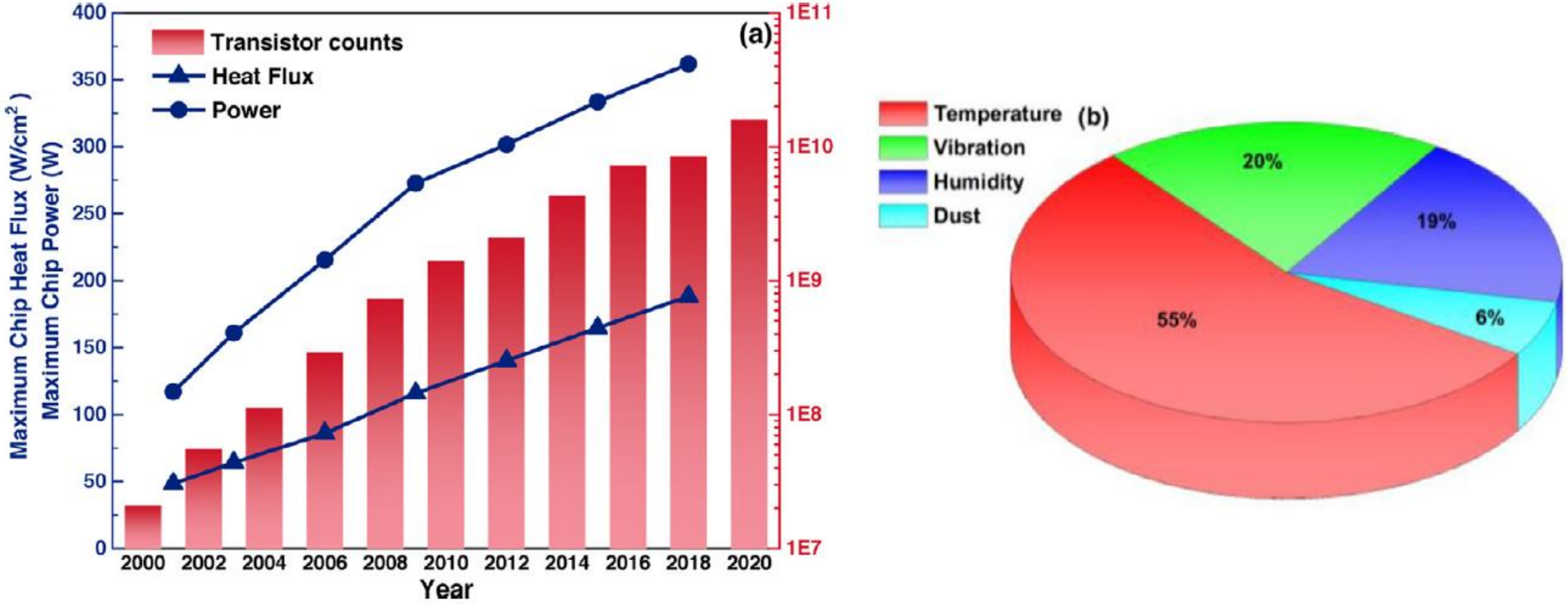
Agenda

- Background
- Design & Concept
- Project Approach
  - Microfabrication
  - Modeling
- Results & Discussion

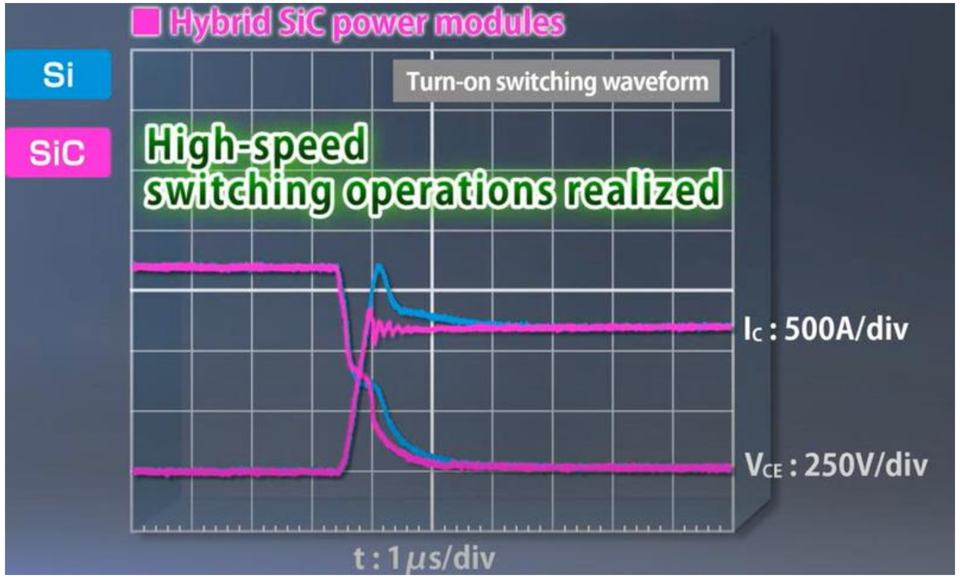
Introduction

- Smaller, lighter, thinner electronic devices
  - Increased power density requirements
  - Greater heat flux density

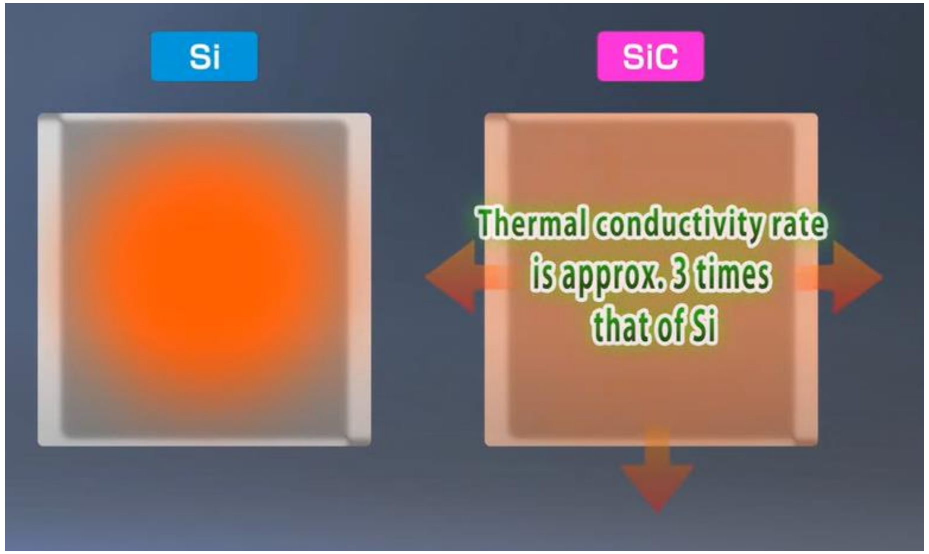


[1] Zhang et al. “A review of the state-of-the-art in electronic cooling”

Silicon vs. SiC



SiC Power Devices [Mitsubishi Electric]

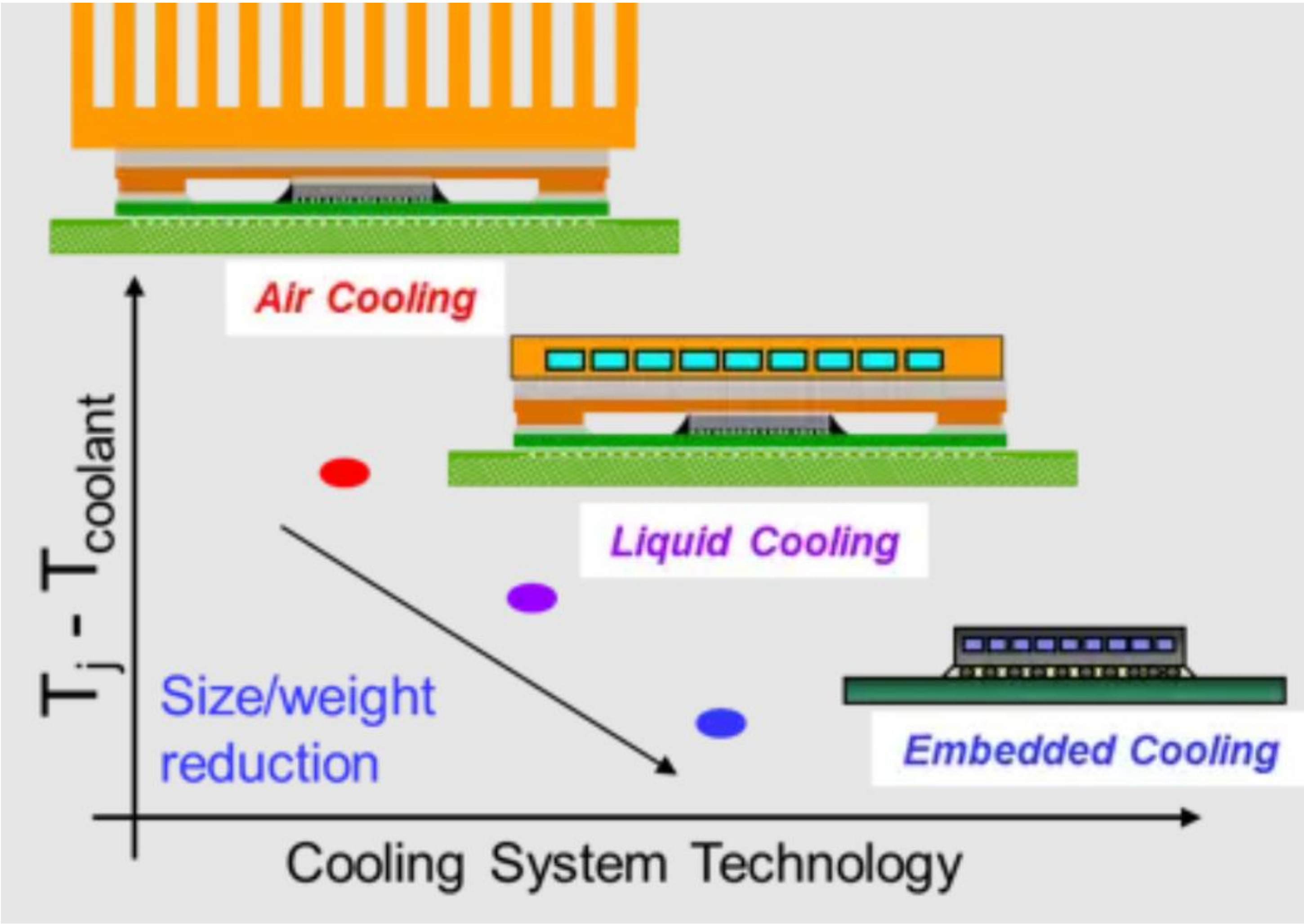


Motivation

- Efficient thermal management technologies to improve performance, function, and reliability of high-powered electronics
  - Prevent from reaching temperature limits
- Develop lightweight thermal management system for compact, high-powered electronics

[2] GRC EAP Technology, Converters

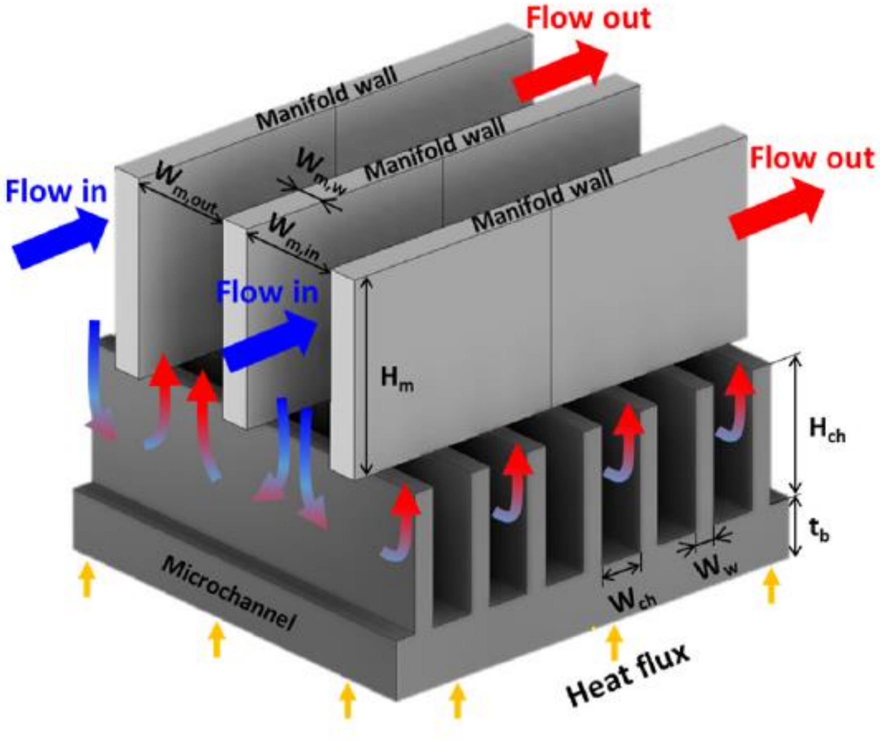
Electronic Cooling Systems



[3] Parida et al., “Beat the Heat in 3D Chip Stacks with Embedded Cooling”

Manifold Microchannel (MMC) Heat Sink

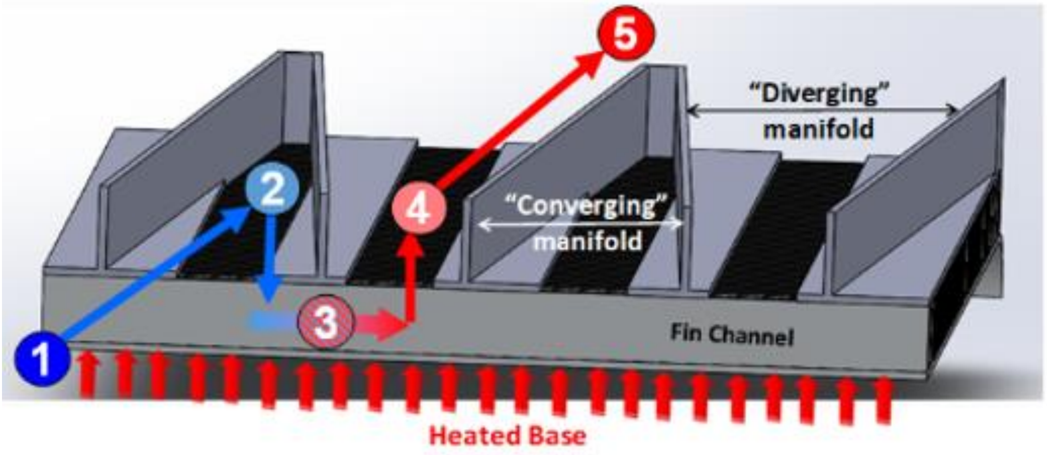
- Strategic way to achieve high heat transfer rates while limiting pressure drop across the heat sink.
- Notable MMC studies
  - Harpole, Eninger (1991) – first study
  - Several parametric studies including
    - Ryu et al., Arie et al., etc.
  - Full 3-D MMC models developed by
    - Boteler et al. (2011) and Kong et al. (2021)
  - Numerical & experimental MMC studies
    - Kermani et al. (2009), Cetegen (2011)
    - Jung, Kharangate et al. (2016)



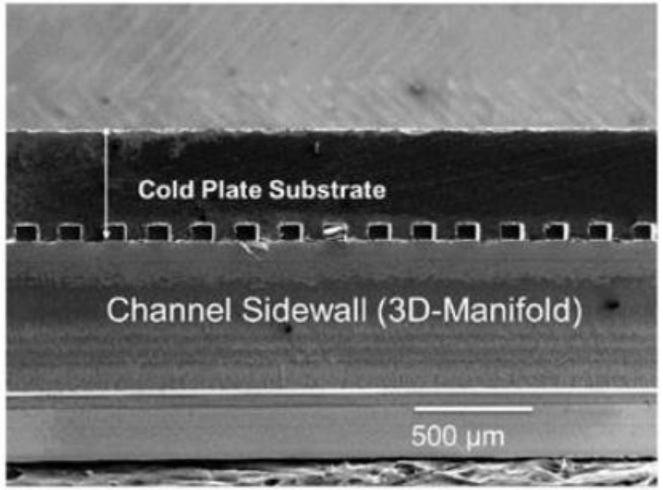
MMC Heat Sink Schematic [Kong et al.]

MMC Design

- Additive manufacturing techniques adapted from previous research
  - Jung, Kharangate et al. (2016) – manufacturing and bonding technique
  - Embedded silicon MMC



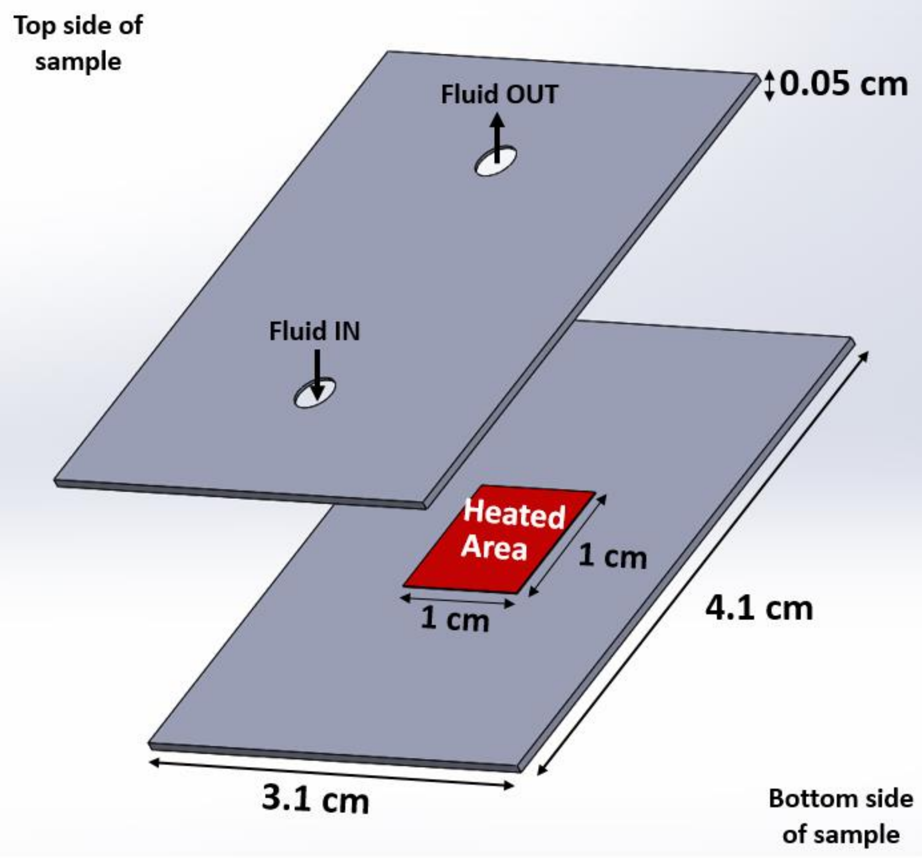
MMC Schematic with fluidic routing



Silicon-based 3-D MMC sample
[Jung, Kharangate et al.]

MMC Concept

- Microfluidic cooling solution that can meet heat dissipation targets of 100 W/cm2 for SiC-based electronics
  - Low thermal resistance (< 1 K/W)
  - Low pressure drop (~1 kPa)
- Two SiC wafers, 350 um thick
  - Manifold & microchannels in separate wafers
  - Fluid inlet and outlet on top wafer
  - Thin film heater on backside of sample
- Integrate sample into flow loop for testing using single-phase working fluids.



Schematic of MMC Sample

MMC Dimensions

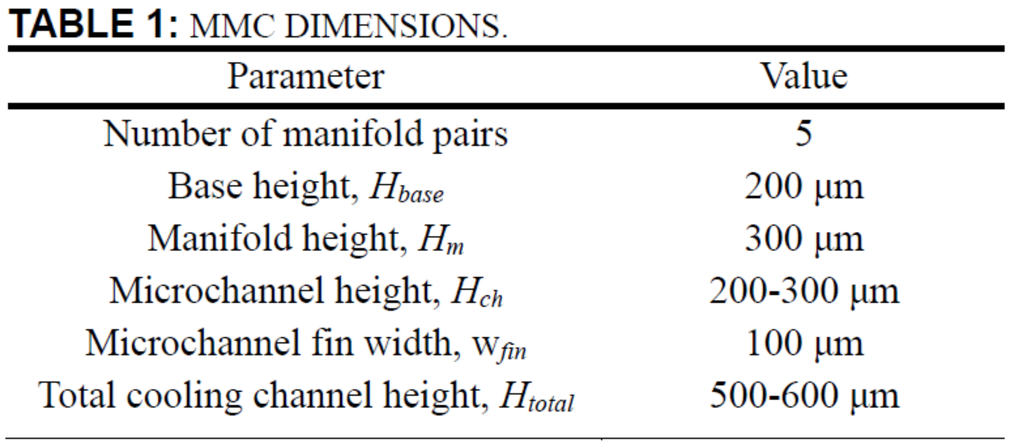
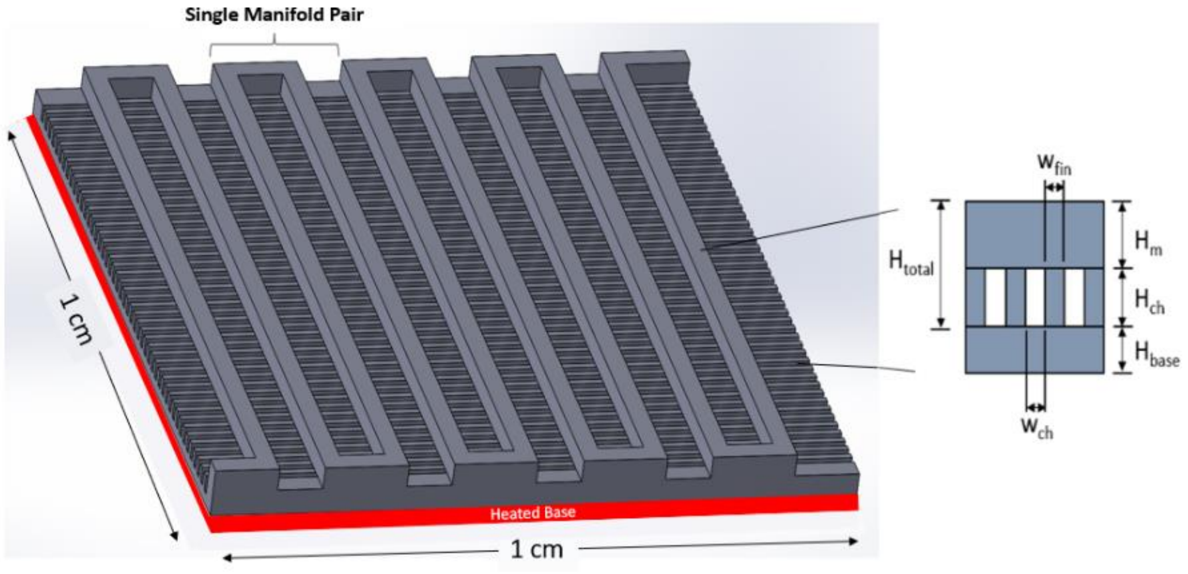


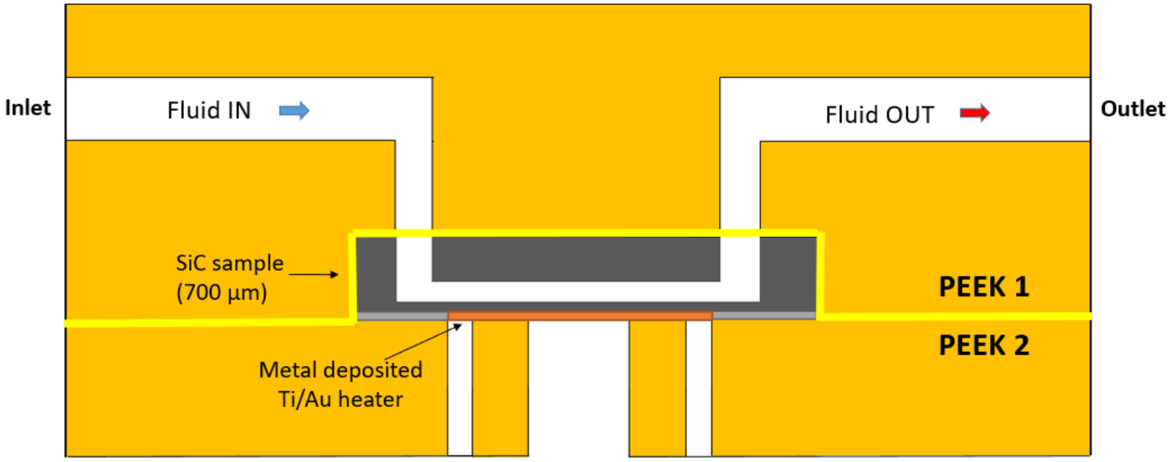
TABLE 1: MMC DIMENSIONS.

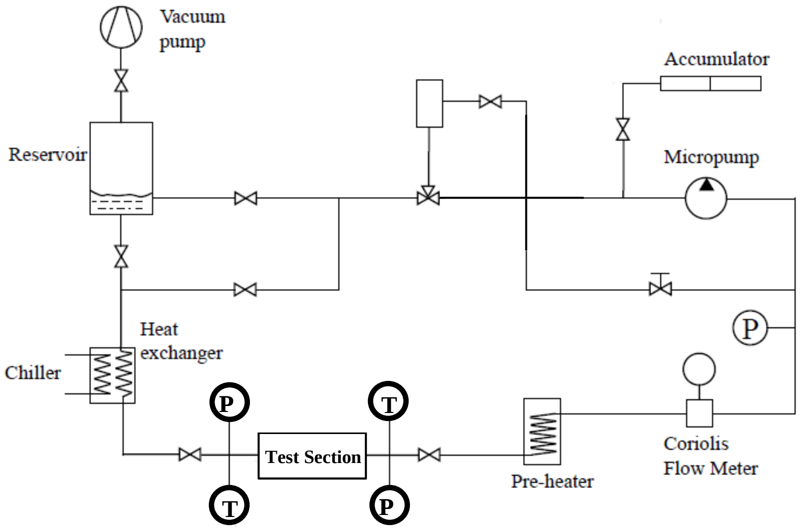
Parameter	Value
Number of manifold pairs	5
Base height, H_{base}	200 µm
Manifold height, H_m	300 µm
Microchannel height, H_{ch}	200-300 µm
Microchannel fin width, w_{fin}	100 µm
Total cooling channel height, H_{total}	500-600 µm

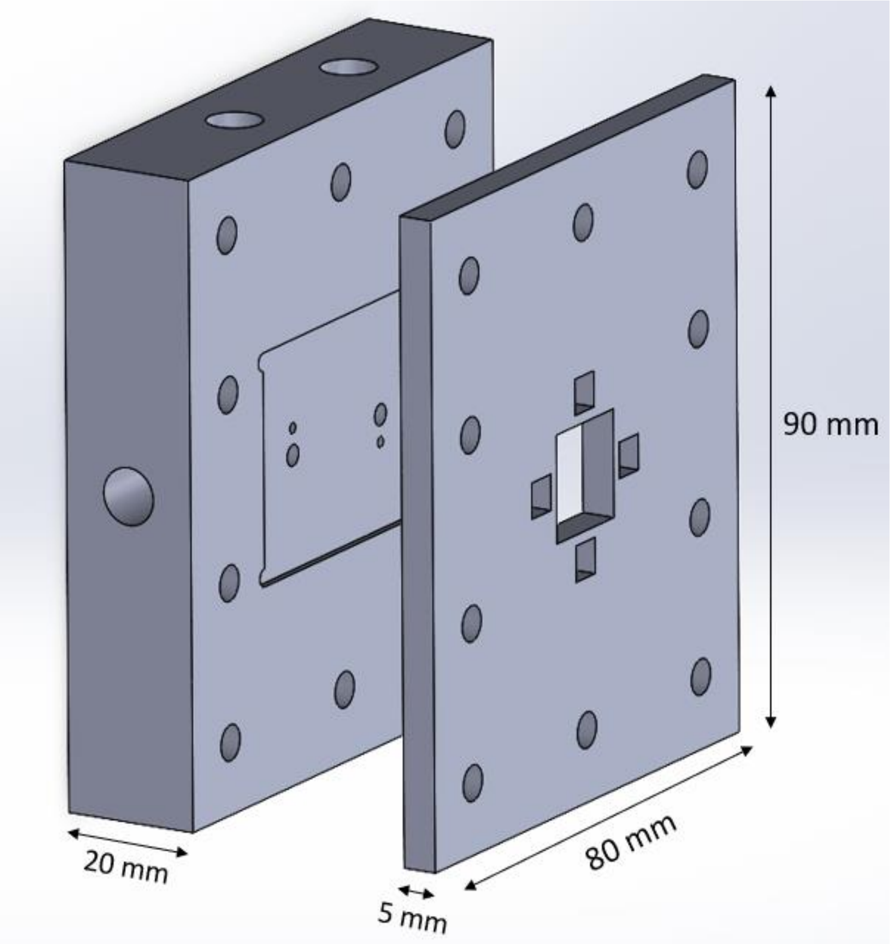


MMC Sample (internal view)

Flow Loop Integration



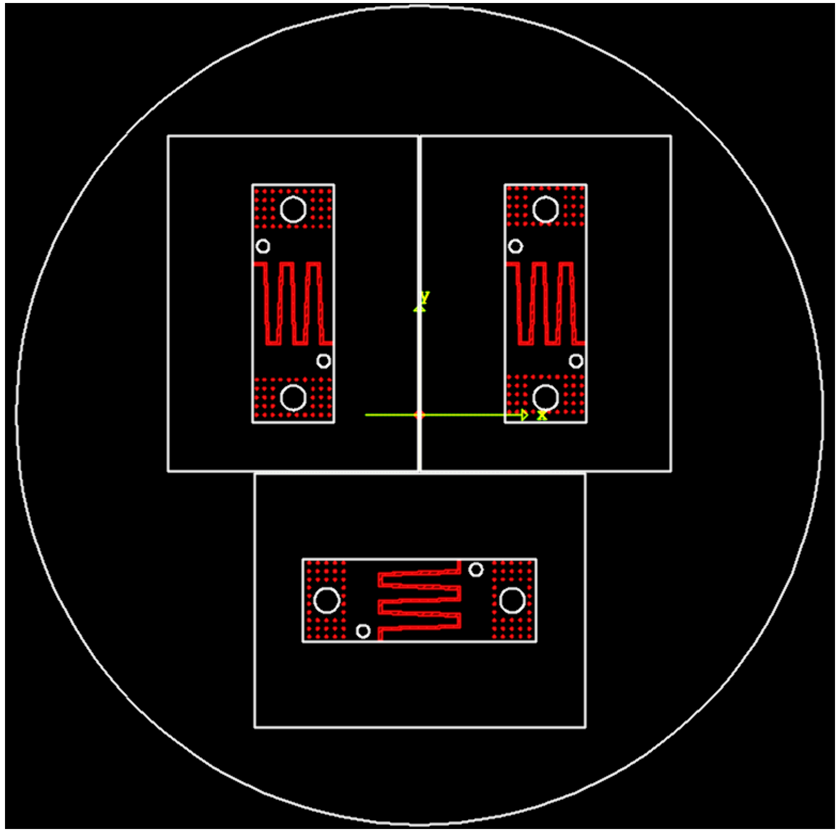




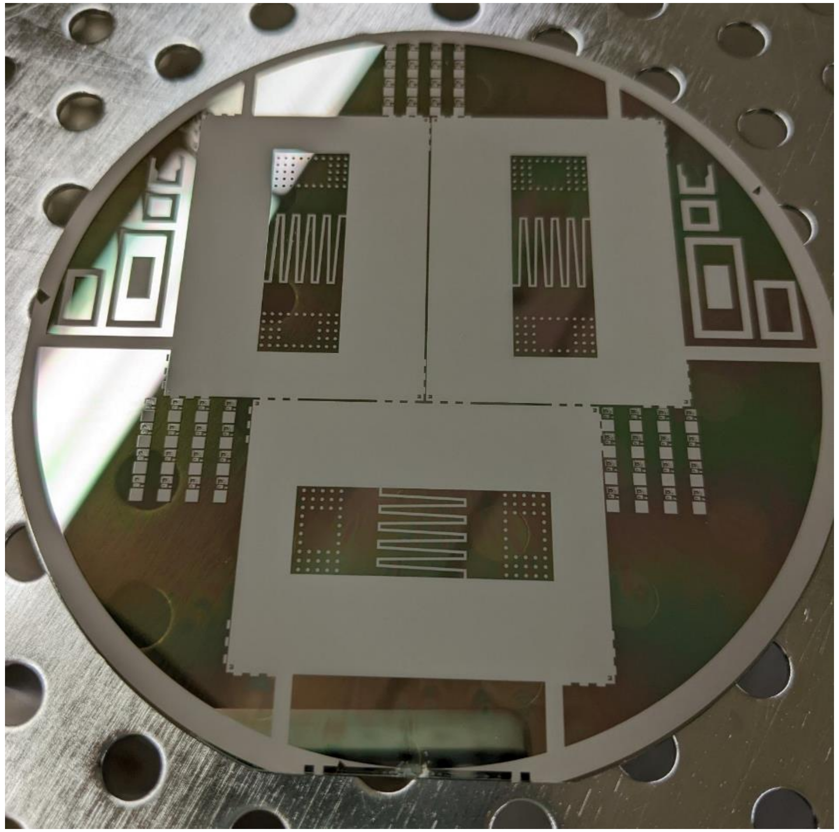
Test Section Sample Holder

PROJECT APPROACH

Microfabrication Process



Photomask Drawing – 3-Manifold



Photomask Pattern on Wafer

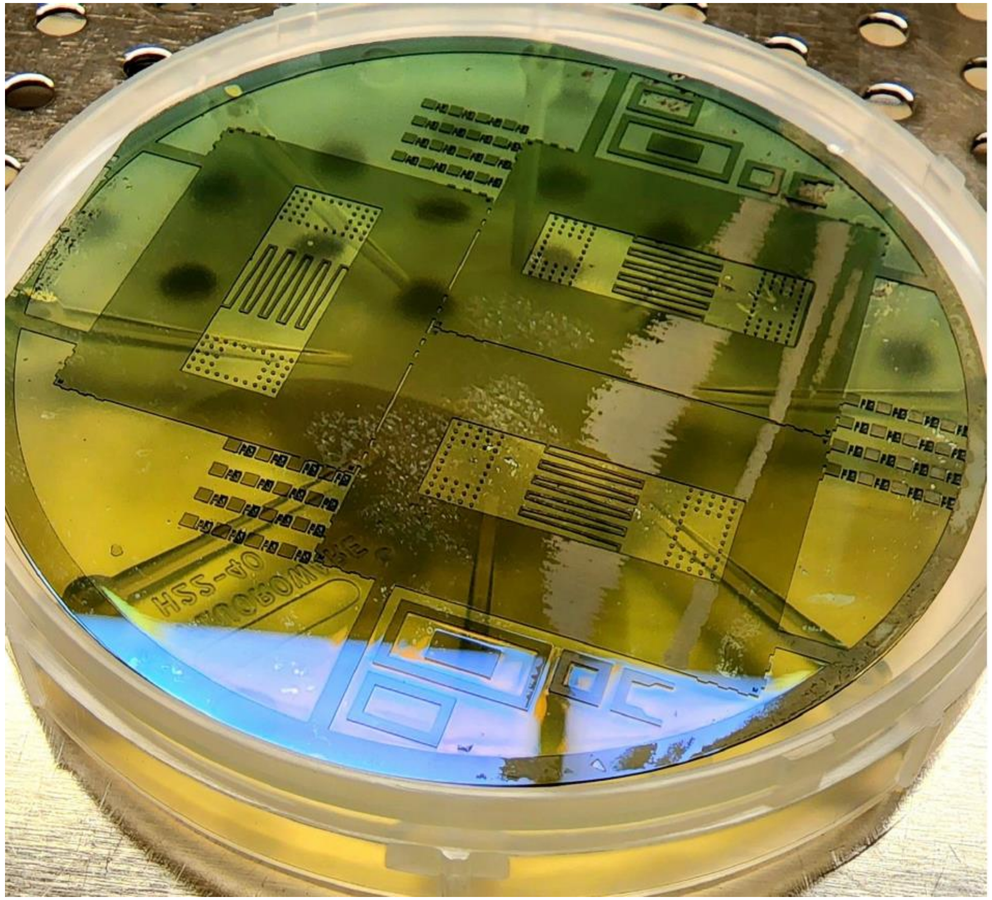
NASA GRC Microsystems Fabrication Laboratory

- 3000-sq-ft. ISO 5 & 6 Cleanroom Space
  - SiC semiconductor R&D facility - IC electronics & sensors
- Various processes & machines for microfabrication
  - Oxford Instruments: Inductively Coupled Plasma (ICP) Reactive Ion Etcher
    - High ion density ($\geq 10^{11}/\text{cm}^3$), low pressure operation (10-90 mTorr)
    - High etch rate: ~1 μm/min, (50/50 SF_6/Argon)

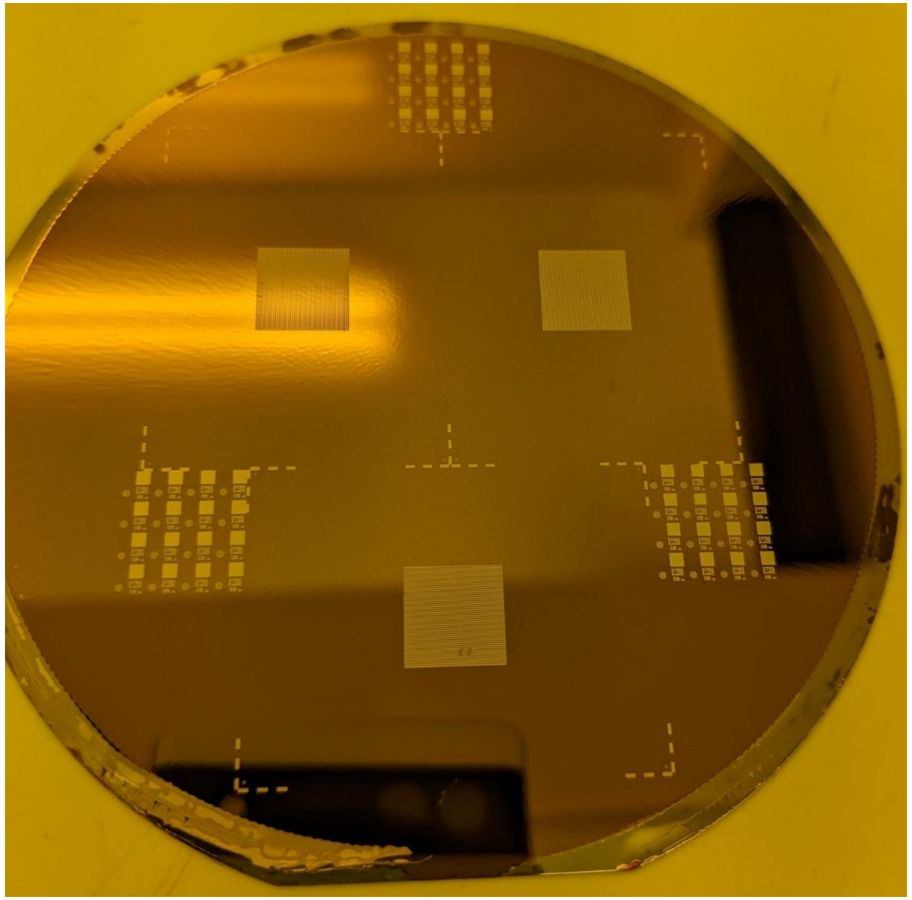
R312 Four Stack Furnace for Bonding

Oxford PlasmaPro 100 Cobra ICP RIE

Fabricated Wafers

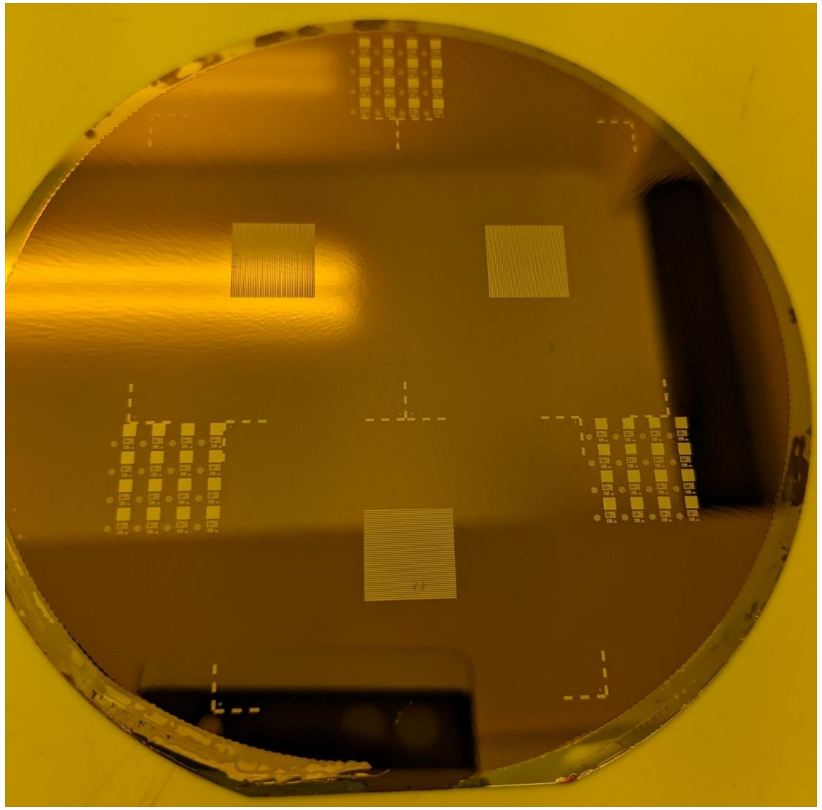


5-Manifold Pattern

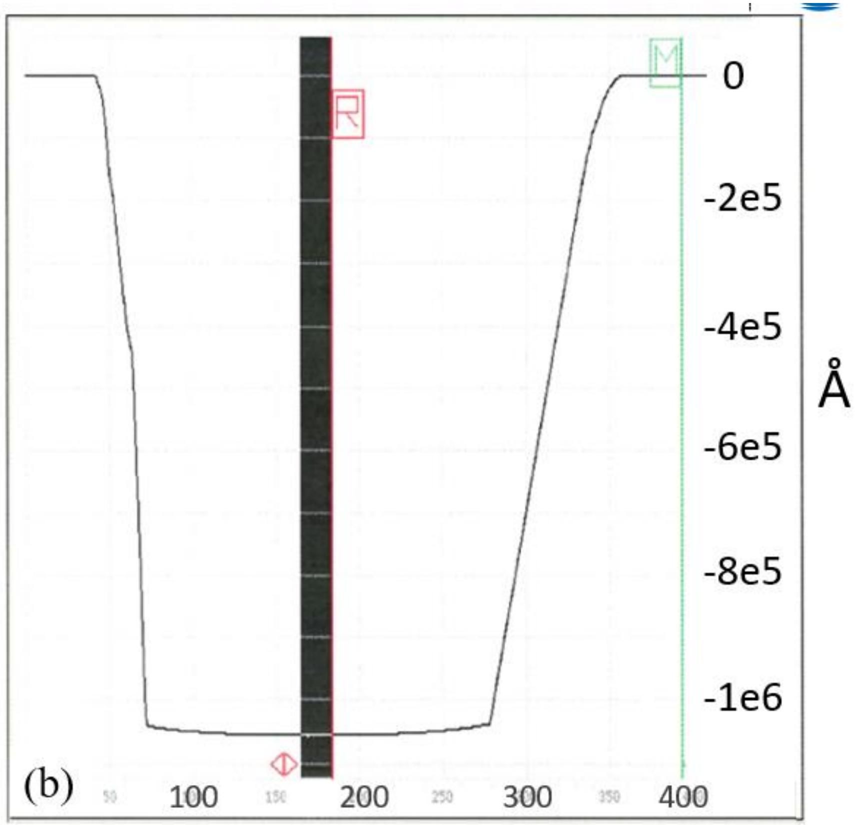


Microchannels

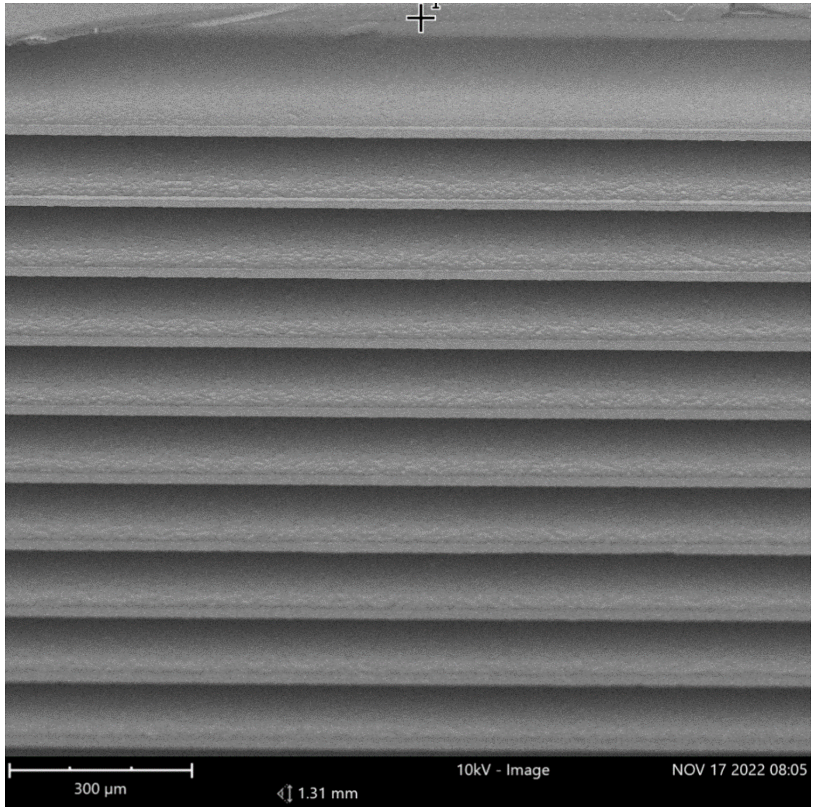
Microchannels



Wafer fabricated with microchannels



Surface Profilometer Reading



SEM Screenshot of Sidewalls (100 μm view)

Reduced-Order Modeling

- Flow parameters used to model and simulate fluid flow through the MMC
- Used REFPROP and equations of state to calculate various flow parameters

$$Nu = 0.1165 \left(\frac{D_h}{L_{ch}}\right)^{0.81} \left(\frac{h_{ch}}{w_{ch}}\right)^{-0.79} Re^{0.62} Pr^{0.33} \quad [6\text{-}7]$$

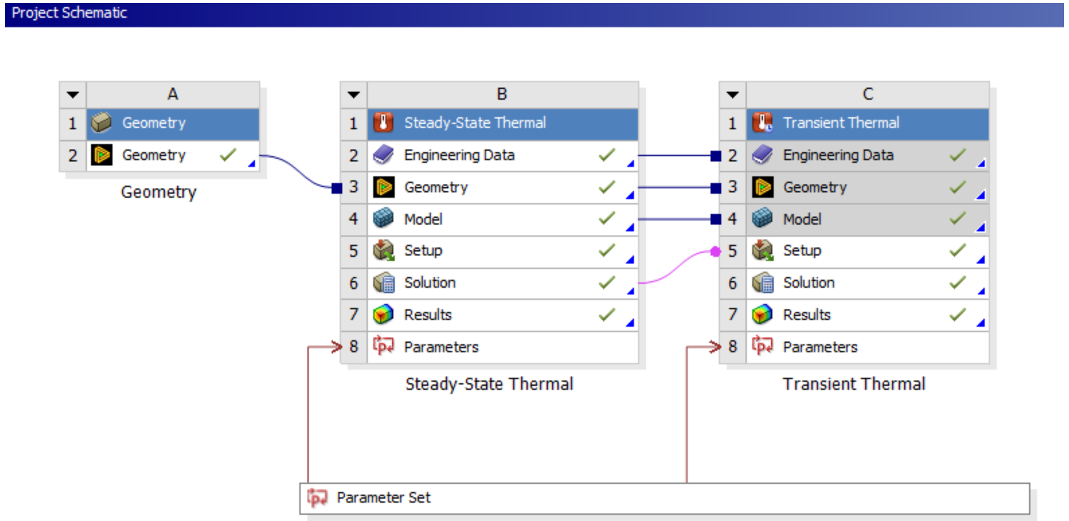
$$\Delta P_{sp,u} = \frac{2 f G^2 L_{ch}}{\rho D_h}$$

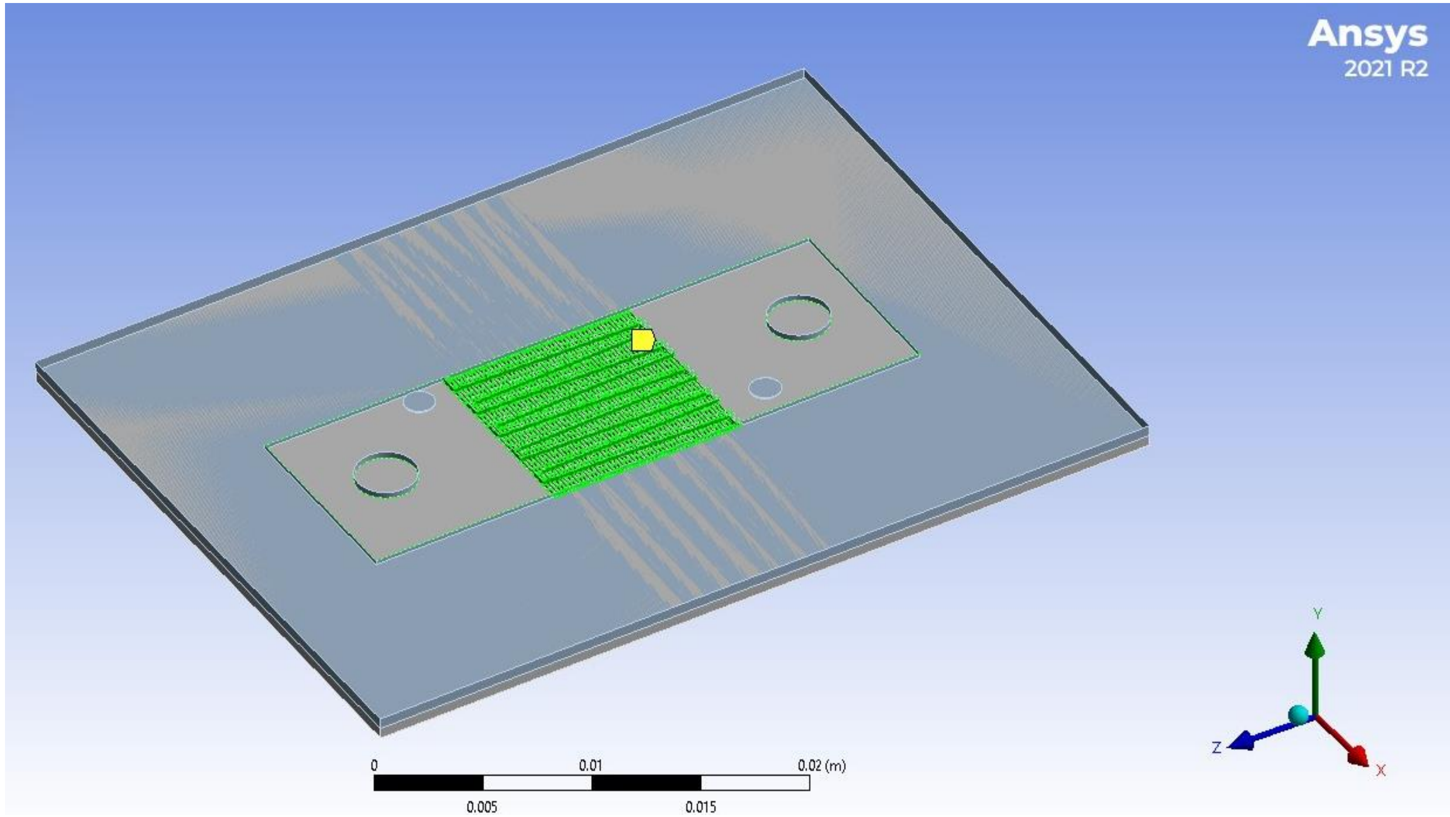
$$h_{sp} = \frac{Nu * k}{D_h}$$

$$R_{th} = \frac{T_w - T_{in}}{q" L_{ch} w_{ch}}$$

Ansys Modeling

- Thermal & fluid models developed - Ansys Fluent & Ansys Mechanical
  - Water, T_{in} = 25 C, ambient pressure
  - Laminar flow through test section
  - 100 W/cm^2 heat flux

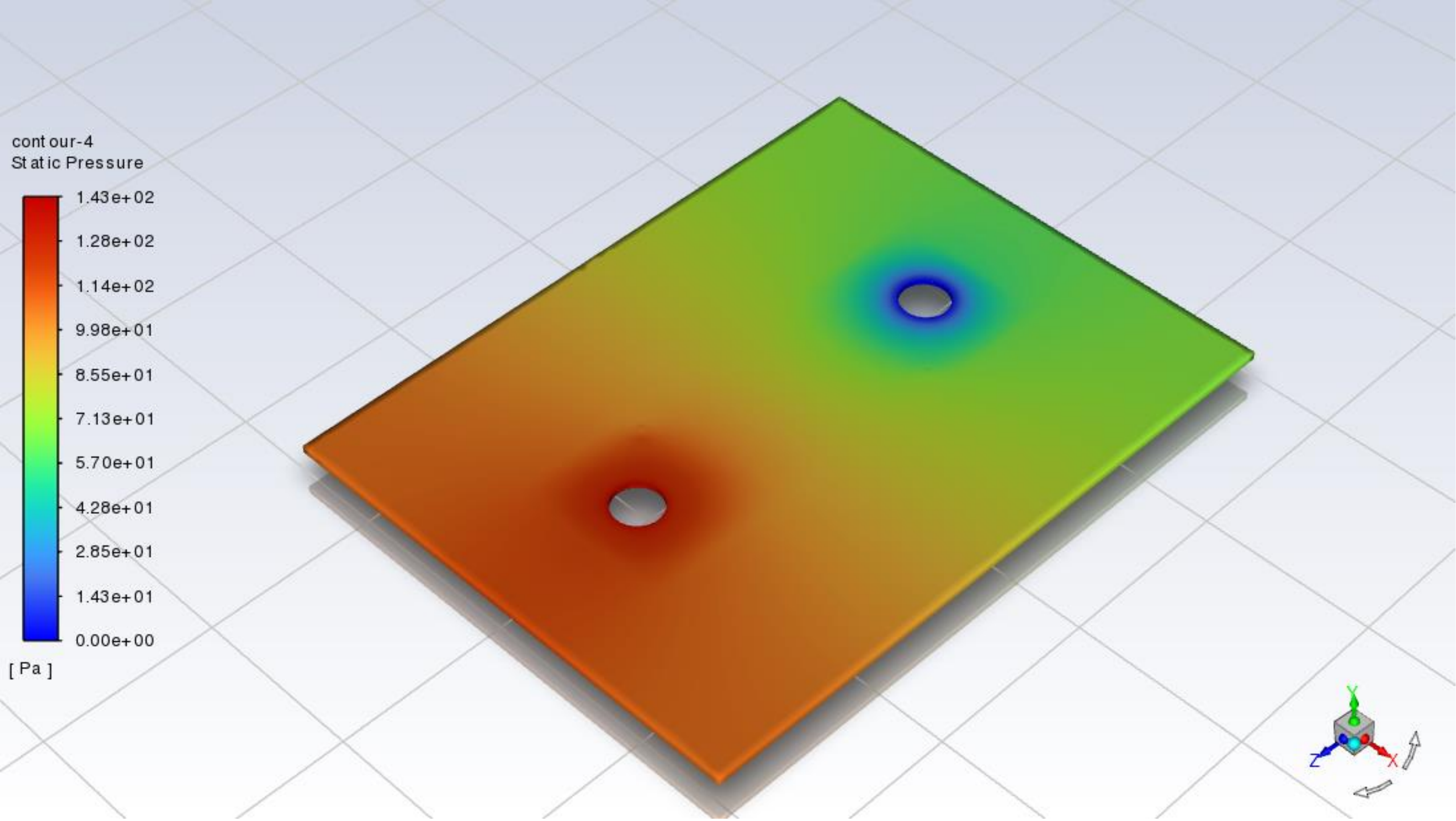




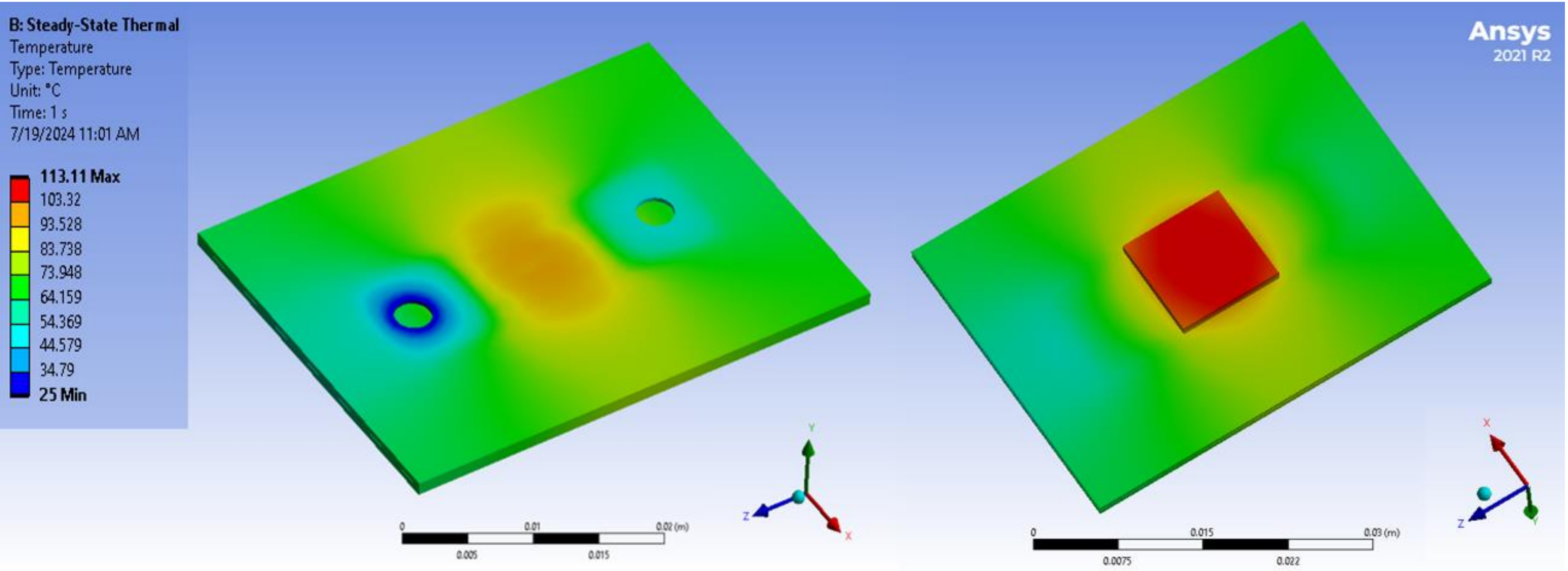
MMC Geometry (test section highlighted)

RESULTS

Results: Fluent Analysis

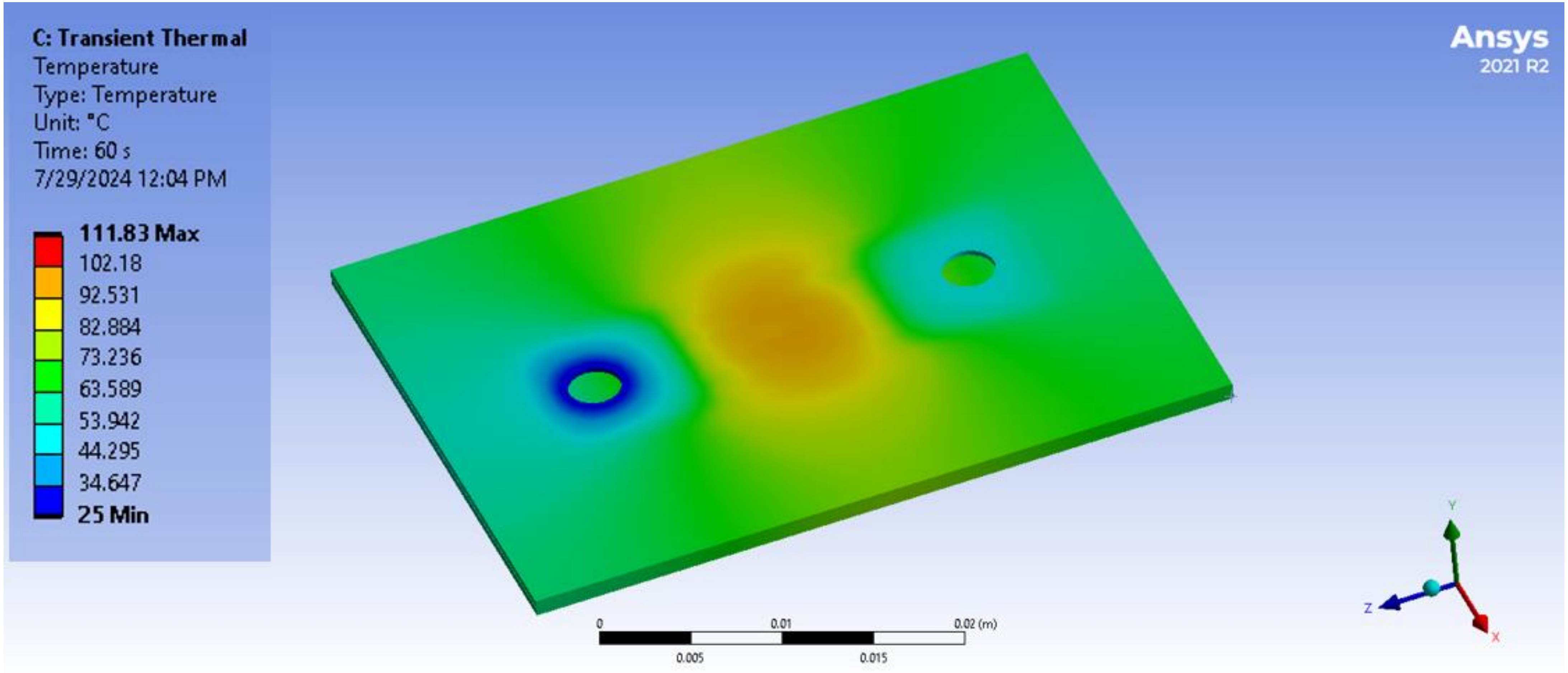


Results: Steady-State Thermal Analysis



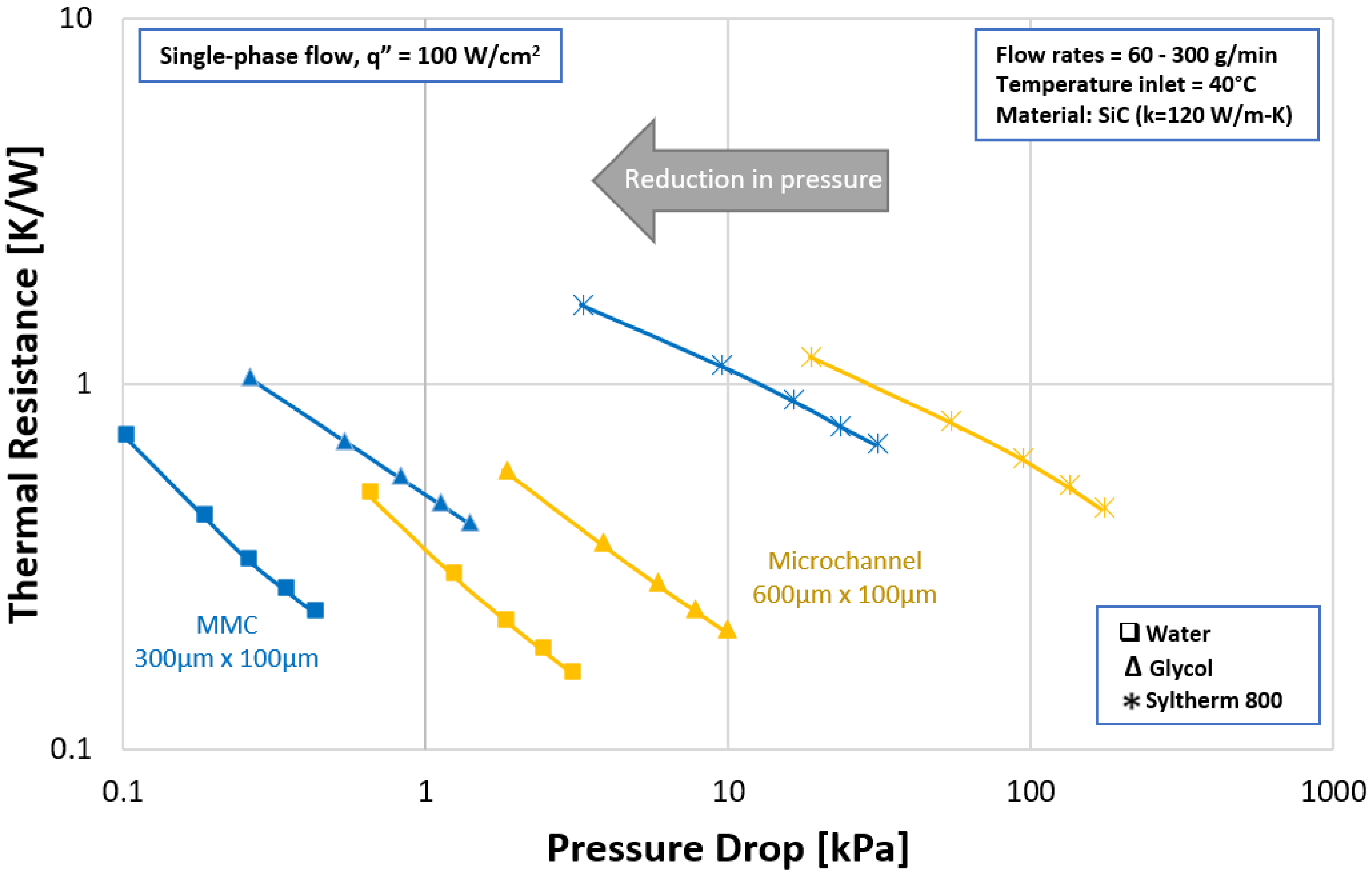
B: Steady-State Thermal
Temperature
Type: Temperature
Unit: °C
Time: 1 s
7/19/2024 11:01 AM

Results: Transient Thermal Analysis

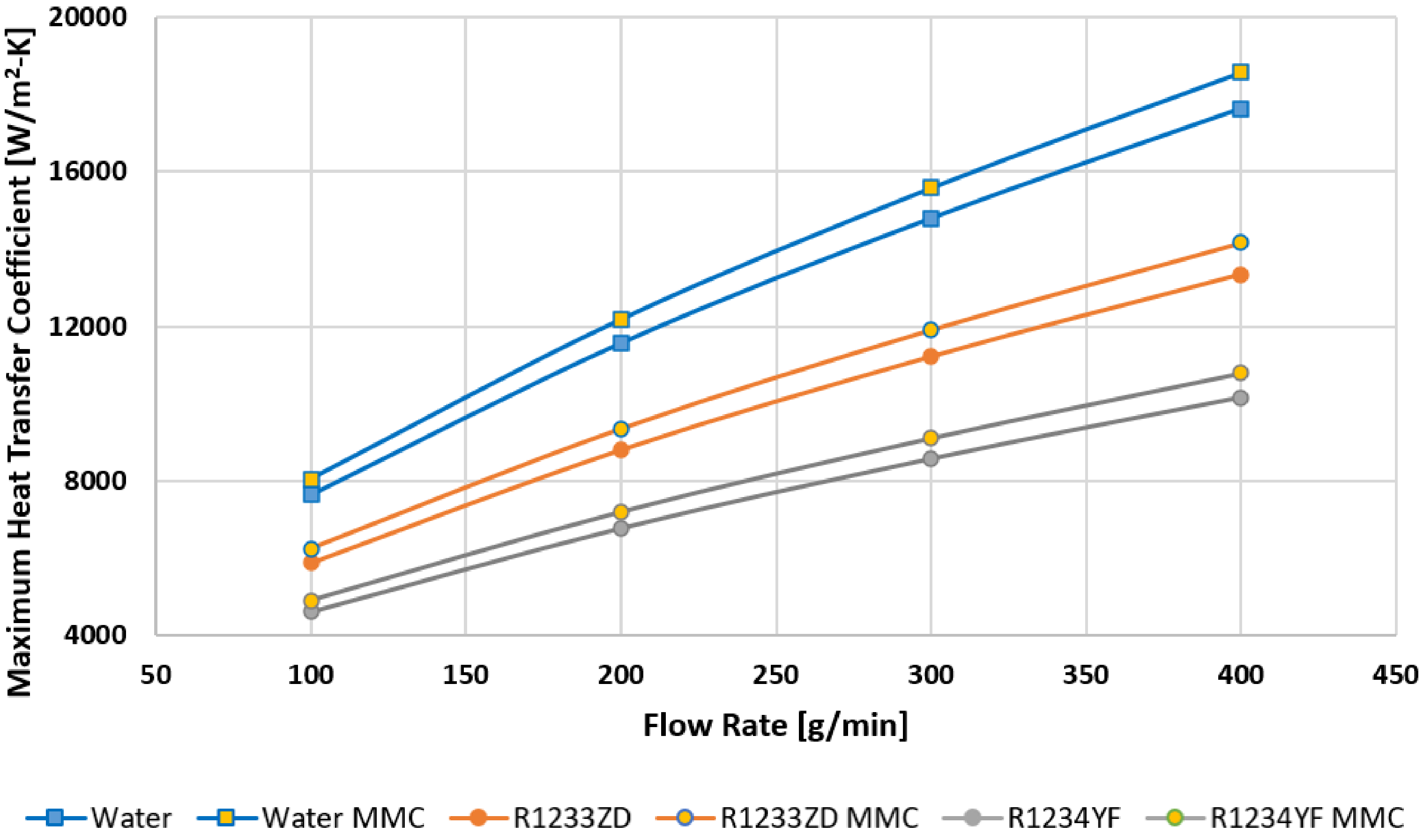


C: Transient Thermal
Temperature
Type: Temperature
Unit: °C
Time: 60 s
7/29/2024 12:04 PM

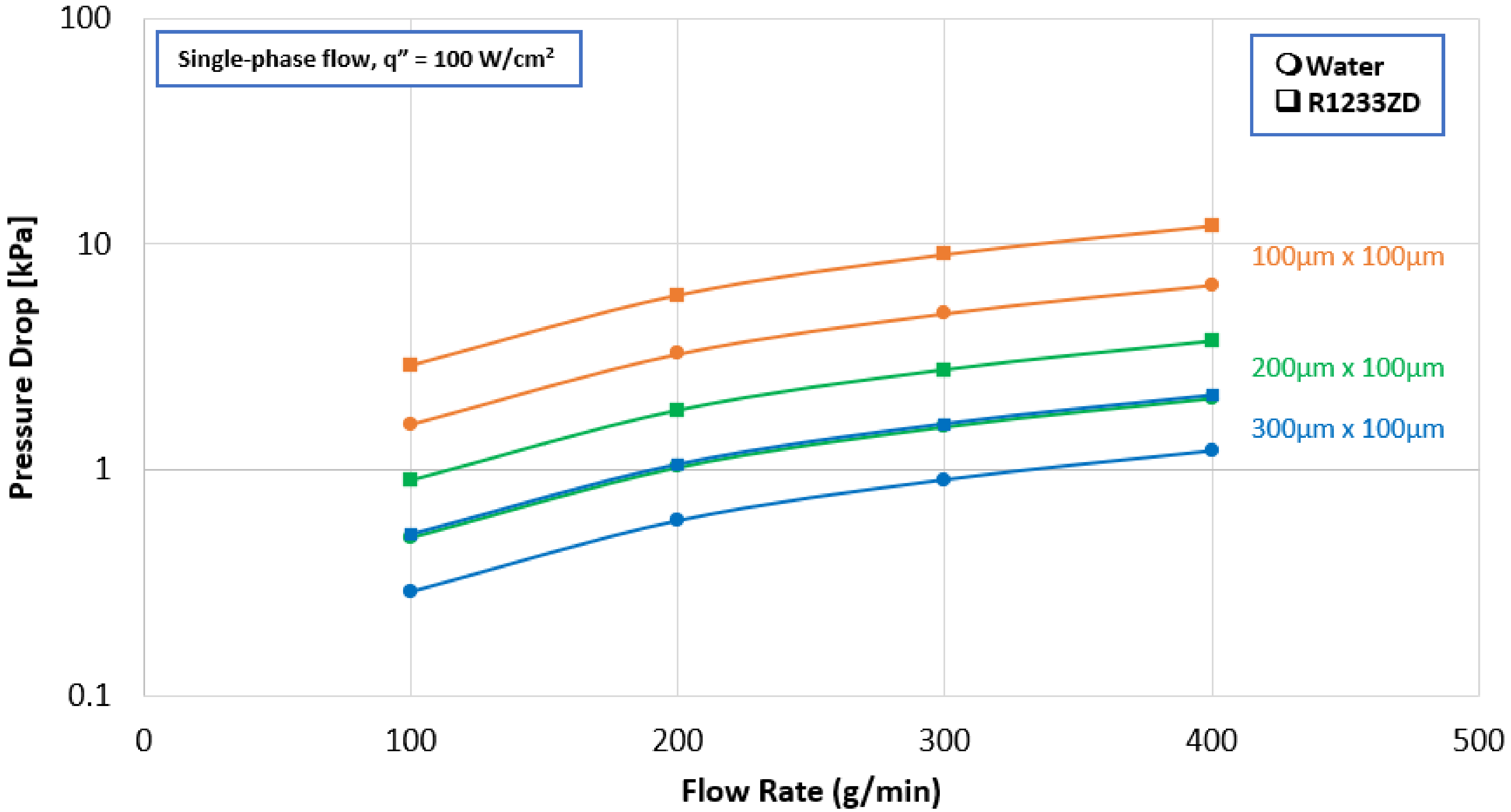
Results


Single-phase flow, q" = 100 W/cm²
Flow rates = 60 - 300 g/min
Temperature inlet = 40°C
Material: SiC (k=120 W/m-K)
Reduction in pressure
Microchannel
600µm x 100µm
MMC
300µm x 100µm
❑ Water
Δ Glycol
✱ Syltherm 800
Thermal Resistance [K/W]
10
1
0.1
Pressure Drop [kPa]
0.1
1
10
100
1000

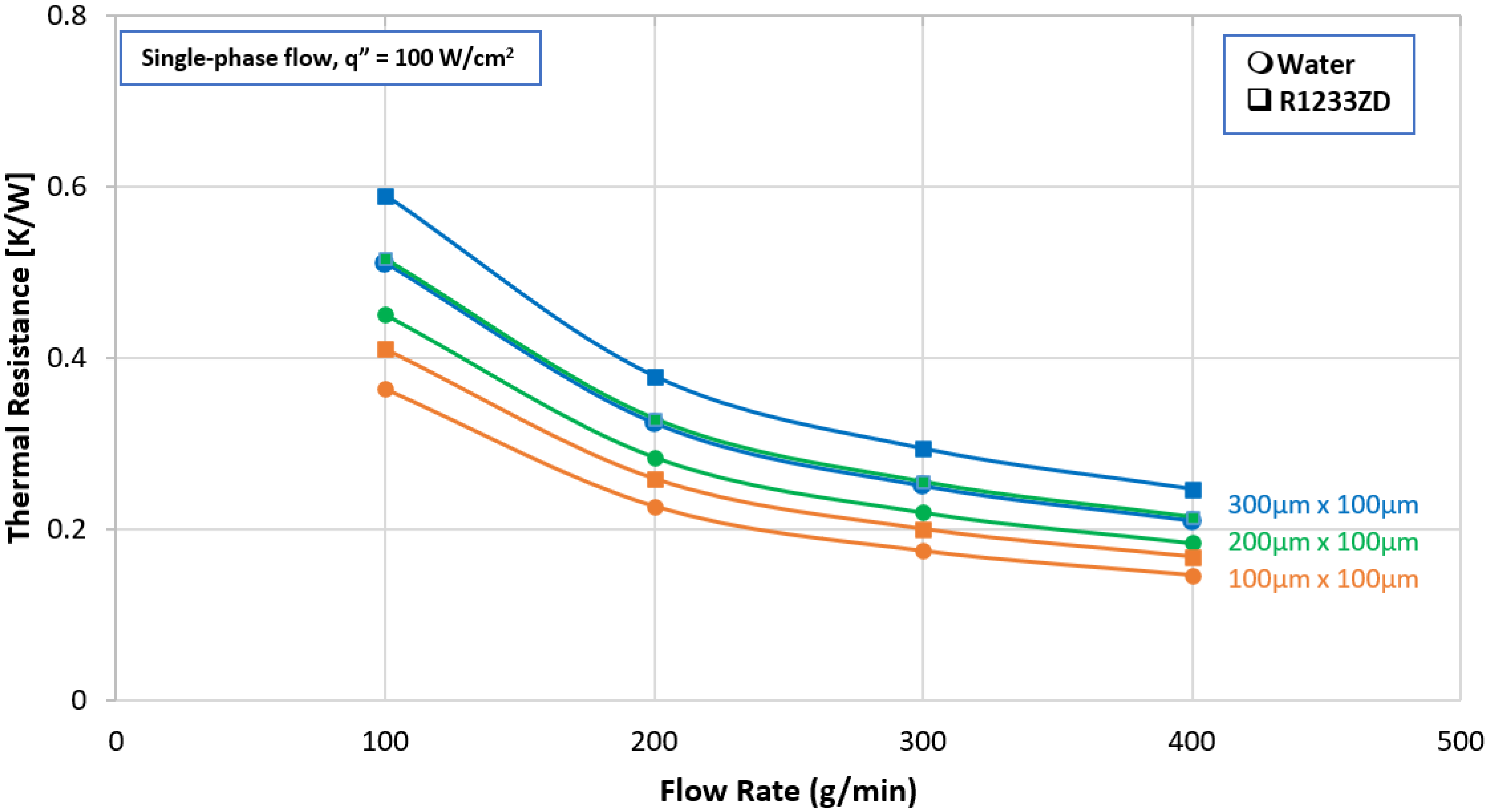
Results


Maximum Heat Transfer Coefficient [W/m²-K]
20000
16000
12000
8000
4000
50
100
150
200
250
300
350
400
450
Flow Rate [g/min]
Water
Water MMC
R1233ZD
R1233ZD MMC
R1234YF
R1234YF MMC

Results: ΔP


Single-phase flow, q" = 100 W/cm²
❍ Water
❑ R1233ZD
100µm x 100µm
200µm x 100µm
300µm x 100µm
Pressure Drop [kPa]
100
10
1
0.1
0
100
200
300
400
500
Flow Rate (g/min)

Results: Thermal Resistance



Conclusions

- For heat dissipation targets of 100 W/cm^2, SiC-based MMC can achieve
  - Low thermal resistance (~ 1 K/W) and low pressure drop (~1 kPa) across the heat sink
  - Certain single-phase working fluids
- Different approaches used to verify MMC performance
  - Fluid & thermal analysis
  - Reduced-order modeling
- Channel height is also a key factor in the MMC performance.
- Next steps
  - Wafer bonding
  - Flow loop testing

References

[1] Zhang, Z., Wang, X., Yan, Y., “A review of the state-of-the-art in electronic cooling”, e-Prime – Advances in Electrical Engineering, Electronics, and Energy, 2021.

[2] SiC Power Devices, Mitsubishi Electric, http://bit.ly/3M8OHDF

[3] Parida, P.R., Schultz, M., Chainer, T., “Beat the Heat in 3D Chip Stacks with Embedded Cooling”, Electronics Cooling, J. Watson Research Center, NY, 2018. https://bit.ly/3B5yJ4V

[4] Kong, D., Kim, Y., Kang, M., Song, E., Hong, Y., Kim, H. S., Rah, K. J., Choi, H. G., Agonafer, D., & Lee, H. “A holistic approach to thermal-hydraulic design of 3D manifold microchannel heat sinks for energy-efficient cooling.” Case Studies in Thermal Engineering (28), 2021.

[5] Jung, K.W., Kharangate, C.R., Lee, H., Palko, J., Zhou, F., Asheghi, M., Dede, E.M., Goodson, K.E. “Embedded cooling with 3D manifold for vehicle power electronics application: Single-phase thermal-fluid performance”, Int. J. Heat Mass Transfer, 2019, 1108-1119.

[6] Kim, S.-M., Mudawar, I. “Consolidated method to predicting pressure drop and heat transfer coefficient for both subcooled and saturated flow boiling in micro-channel heat sinks”, Int. J. Heat Mass Transfer, Vol. 55, 2012, 3720-3731.

[7] Copeland, D., “Manifold microchannel heat sinks: analysis and optimization”, ASME/JSME Thermal Eng. 4 (1995) 169–174.

Acknowledgements

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