



ALLIANCE FOR STRATEGIC SEMICONDUCTOR AND ELECTRONICS TECHNOLOGIES

Laser-Machined Interposer with Diamond-Coated Capillary Surfaces for Hotspot Mitigation in 3D Heterogeneous Integration (3DHI) Packaging

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The Thermal Challenge in 3DHI

Hotspot formation is emerging as the primary thermal bottleneck in advanced 3DHI packages.

- Chip power densities continue to increase
- Heat must travel through vertically constrained pathways
- Local hotspots become performance-limiting
- Conventional spreading approaches struggle at the package scale

Local hotspot heat fluxes can approach hundreds of W/cm^2 in advanced packages.



Why Hotspots Matter

Temperature gradients drive both performance loss and reliability risk.

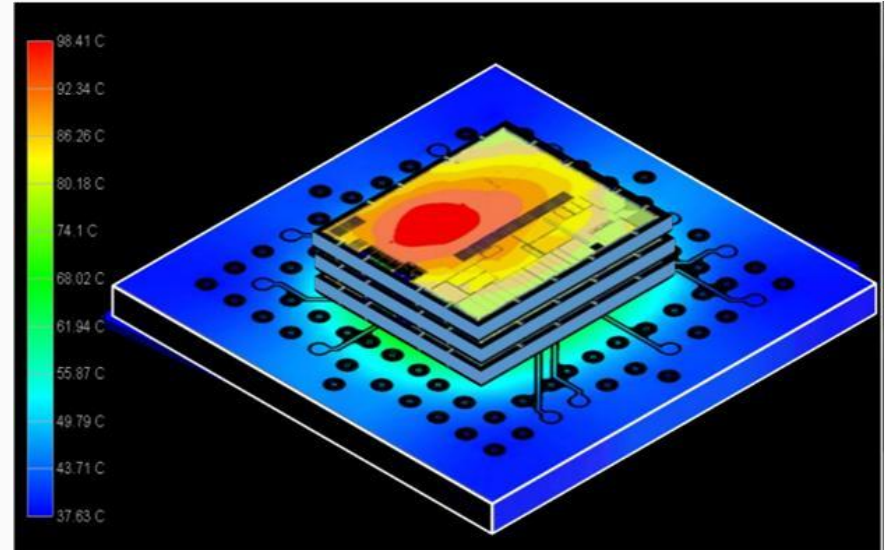
Performance:

- Thermal failure
- Timing delays

Reliability:

- Mechanical stress
- Lifetime reduction

Temperature gradient → Stress → Failure Pathway



Why Existing Solutions Are Not Enough

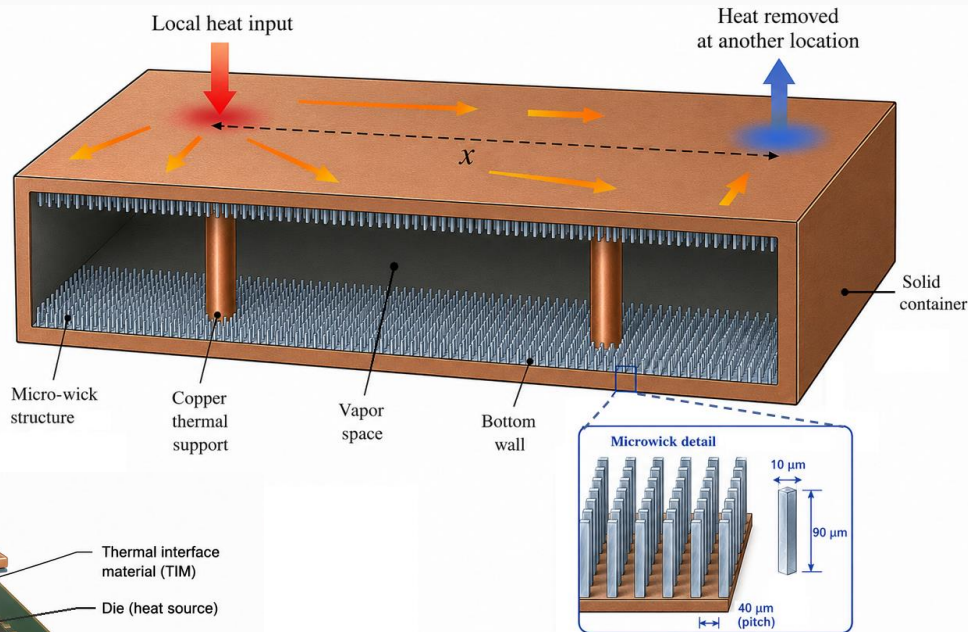
Existing Cooling Approaches:

Technology	Strength	Limitation
Heat spreaders	Mature	Limited hotspot mitigation
Vapor chambers	Excellent spreading	Above-package solution
Microchannels	High HTC	Pumping complexity
Interposer cooling	Close to source	Manufacturing challenge

This motivates cooling architectures that are integrated closer to the heat source.

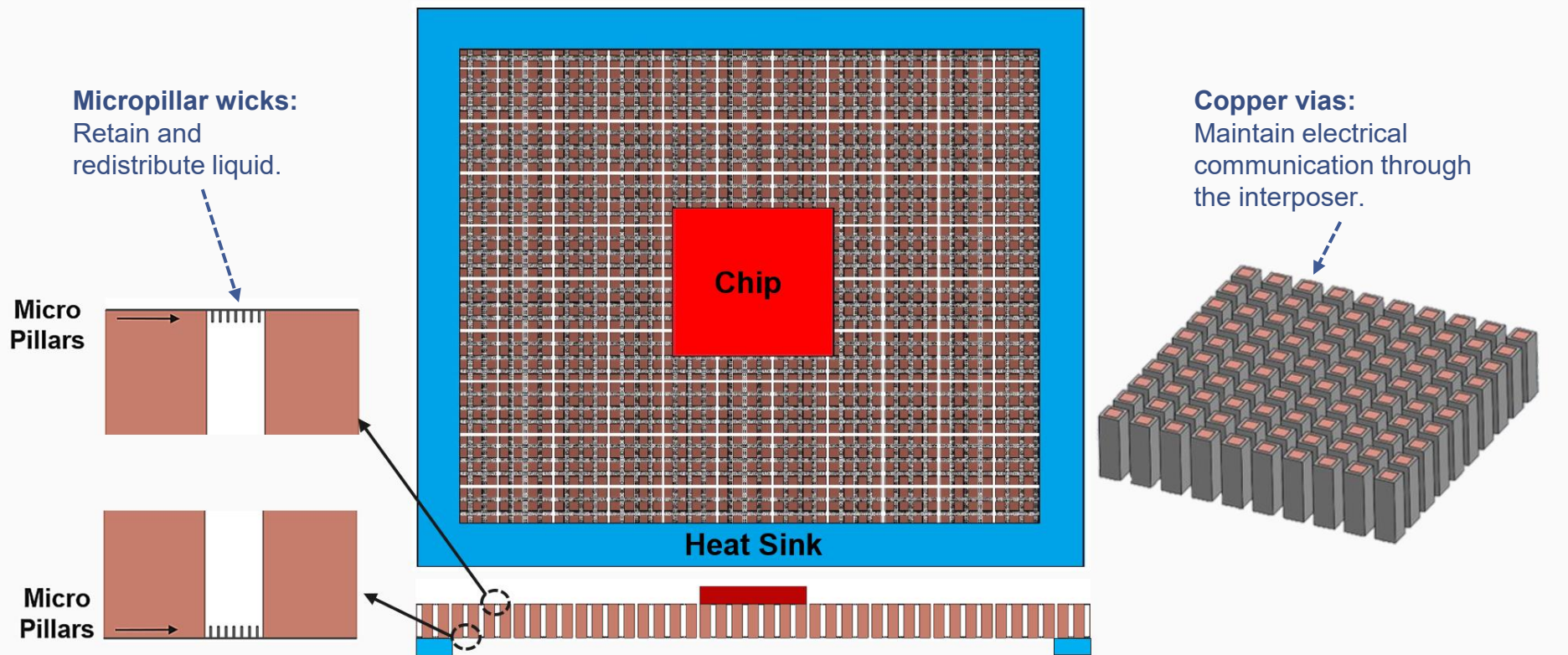
Proposed Solution

A capillary-fed, two-phase thermal pathway is built into the package layer rather than added on top of it.



Target: >20% hotspot temperature reduction within a fixed package footprint

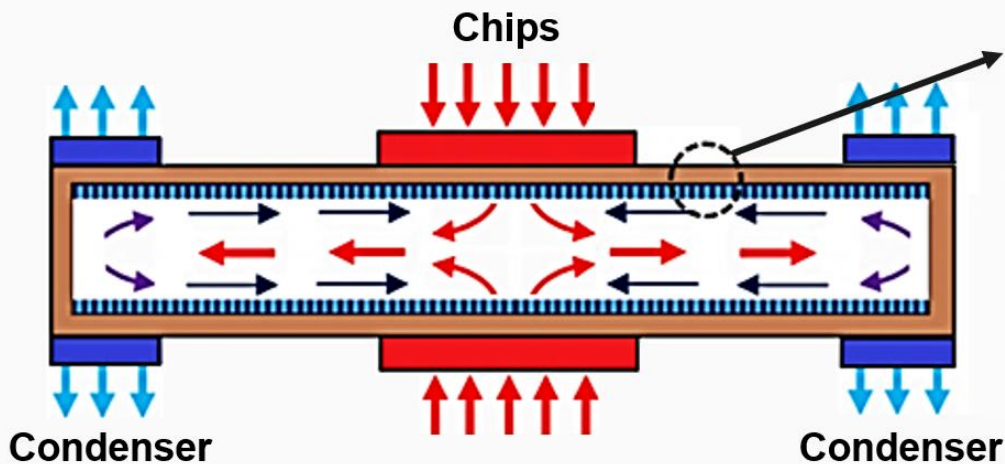
Thermo-Electrical Interposer



Operating Principle

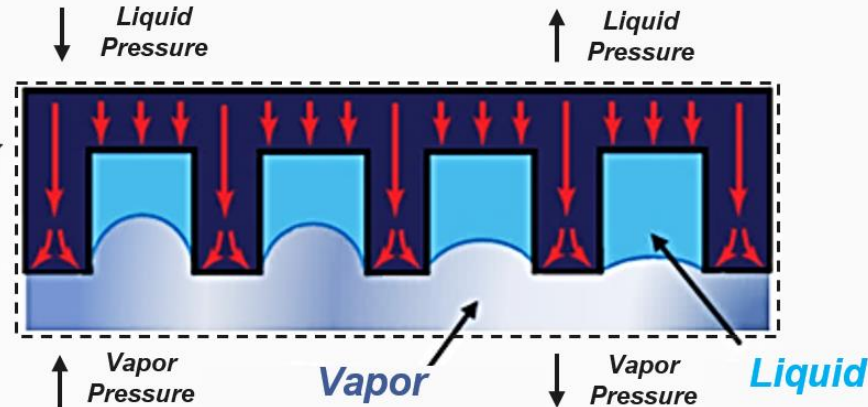
1. Hotspot drives evaporation

2. Vapor spreads heat laterally



3. Condenser rejects heat

4. Capillary wicks return liquid

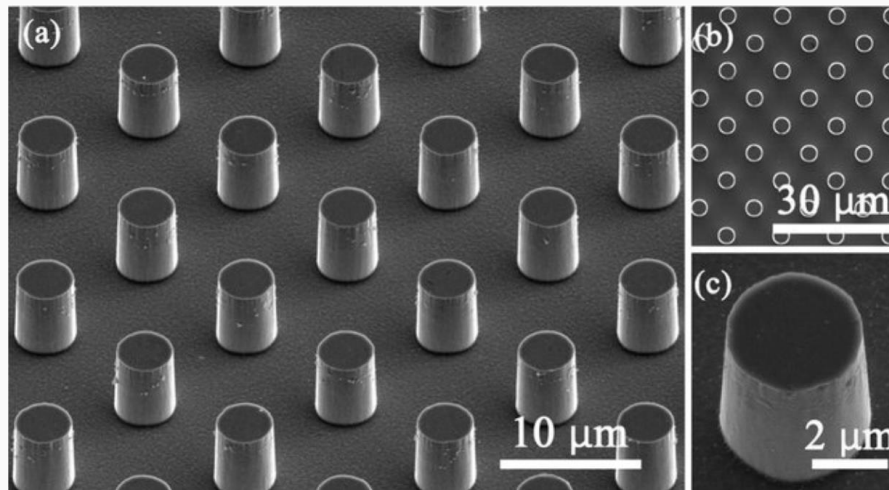


Latent heat transport enables large heat removal at a small temperature rise.

Laser-Manufactured Wick Architecture

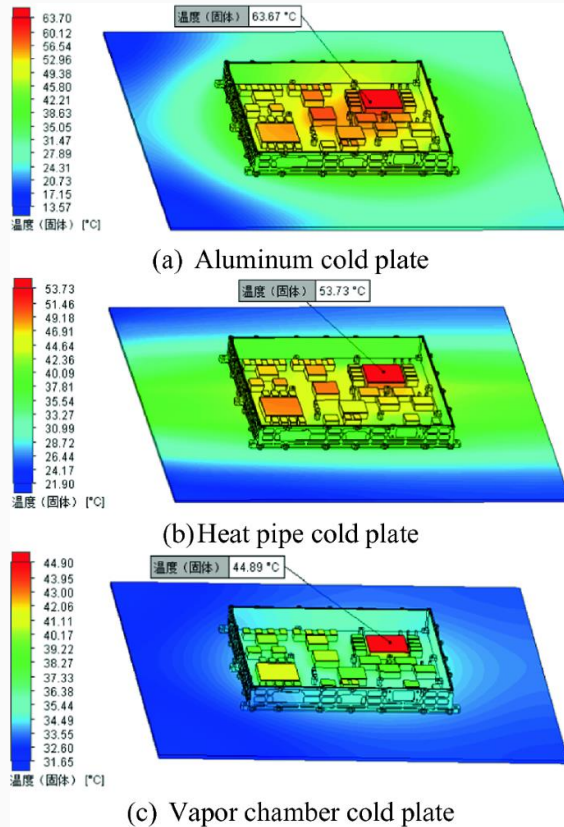
Benefits of laser-manufactured wicks

- **Precisely patterned:** Creates a controllable capillary network.
- **Ordered geometries:** Enable tuning of capillary pressure and permeability.
- **High-aspect ratios:** Increase evaporation area within a thin package footprint.
- **Scalability:** Supports thermal-interposer integration.



With laser processing, we can intentionally design and optimize the fluid transport pathway to mitigate hotspots.

Why Conventional Wicks Fall Short



Capillary vs. Permeability Trade-Off

Small pores:

- High capillary pressure
- High flow resistance

Large pores:

- Low pressure
- Better flow

Material Challenge

Dielectric materials (Alumina) transport liquid well but conduct heat poorly.

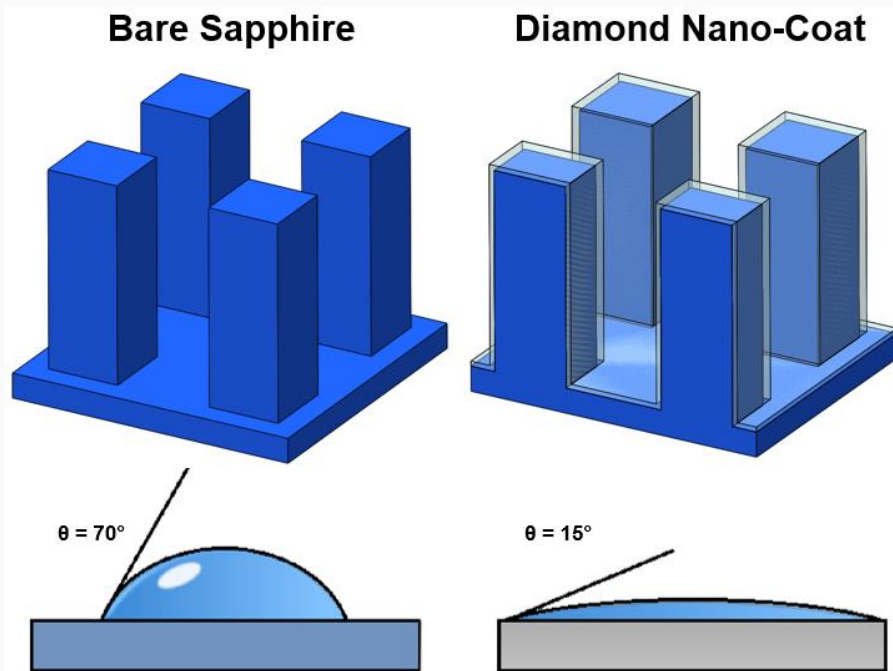
The liquid transport is adequate, but heat cannot efficiently reach the evaporation front.



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Diamond-Coated Wick Concept



Sapphire Substrate:

- Significantly increases structural integrity
- CTE match between sapphire and silicon
- Able to machine via laser etching

Property	Dielectric Wick	Diamond Wick
Wettability	Moderate	Excellent
Thermal Transport	Limited	Enhanced
Dry-out Resistance	Lower	Higher

- **Contact angle** determines surface affinity for liquid
- **Surface coatings** dramatically shift capillary limits

Diamond simultaneously improves liquid spreading and heat delivery to the evaporation interface.

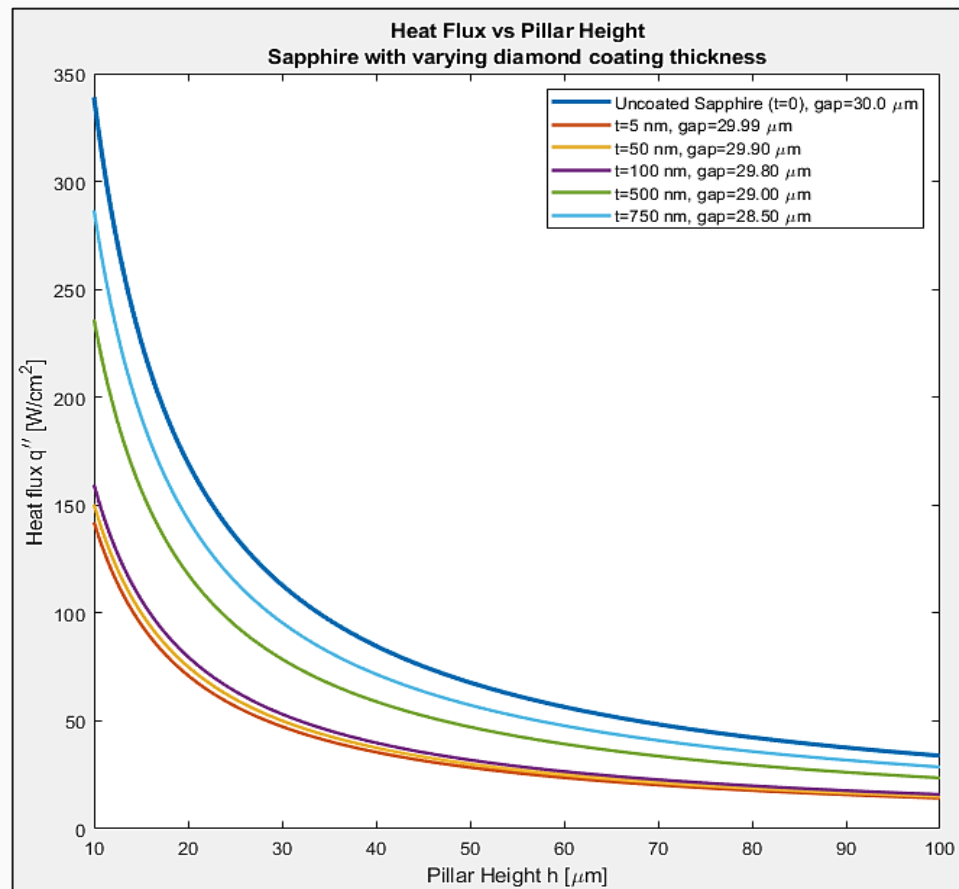
Diamond Coating Conduction Limit

Will diamond coating change internal dimensions?

$h = 90 \mu\text{m}$:

Material	ΔT [K]	k [W/m·K]	q'' [W/cm ²]
Sapphire	12	2.83	37.7
Diamond $t= 5 \text{ nm}$	5	2.84	15.7
Diamond $t= 50 \text{ nm}$	5	3.01	16.7
Diamond $t= 100 \text{ nm}$	5	3.19	17.7
Diamond $t= 500 \text{ nm}$	5	4.72	26.2
Diamond $t= 750 \text{ nm}$	5	5.73	31.8

Nano-layer diamond significantly **improves** interfacial transport **without** increasing device thickness.



Comparison of Wicking Structures

Feature	Sintered Alumina Wick	Sintered Copper Wick	Sapphire + Nano-Diamond
Thermal Conductivity	Very Low (< 10 W/mK)	High (50- 100 W/mK)	Superior Dielectric Performance Sapphire Base: 40 W/mK (Solid) Diamond Skin: 200- 1000 W/mK (Surface)
Capillary Effects	Random Pore Structure High flow resistance; difficult to optimize.	Random Pore Structure Good capillary force; high flow resistance.	Ordered/Precise Geometries Allows mathematical decoupling of permeability from capillary pressure.
Heat Transfer	Poor Insulates the working fluid from the heat source.	Efficient Conducts heat well to the evaporation interface.	Hyper-Efficient Diamond layer spreads heat laterally at the <i>micro-level</i> to prevent "hot spots."
Durability	Brittle Prone to cracking and particle generation (clogging).	Ductile but Soft Can deform under pressure; chemical erosion over time.	Extreme Chemically inert, erosion-proof, and structurally rigid.

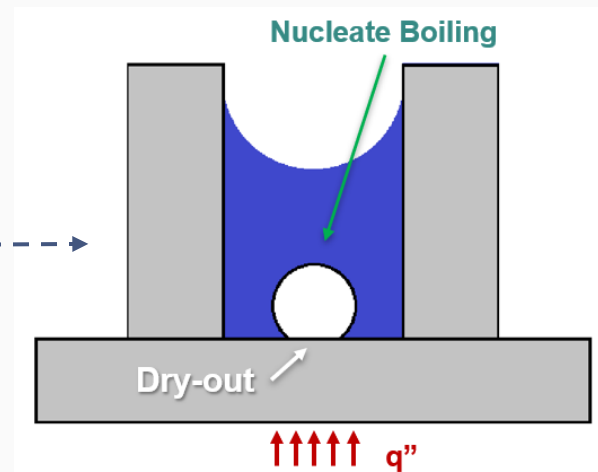
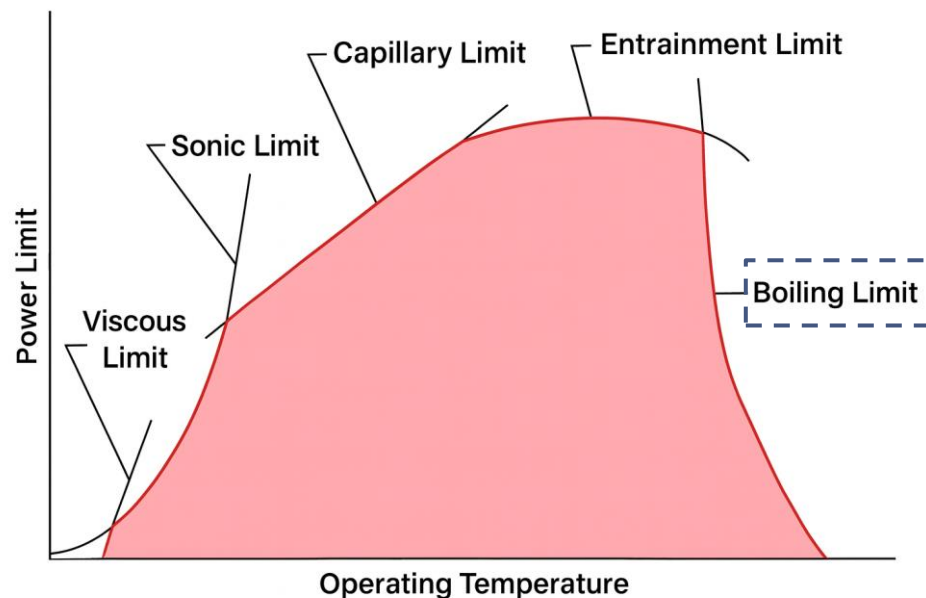
Diamond-enhanced laser-manufactured wicks combine controllable fluid transport with improved thermal transport and structural integrity.

What Ultimately Limits Performance?

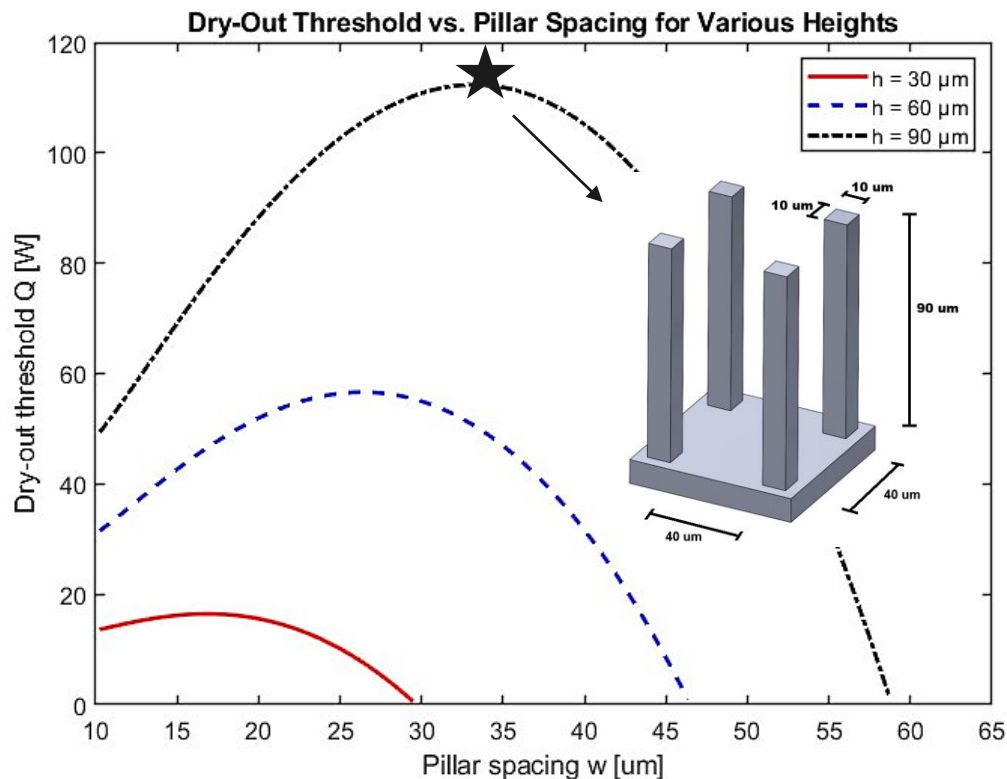
Dry-out:

- Liquid supply cannot match evaporation demand
- Capillary pressure must overcome liquid and vapor losses
- Once dry-out occurs, cooling performance rapidly degrades

*If nucleate boiling occurs within the micro pillar array, liquid transport **fails***

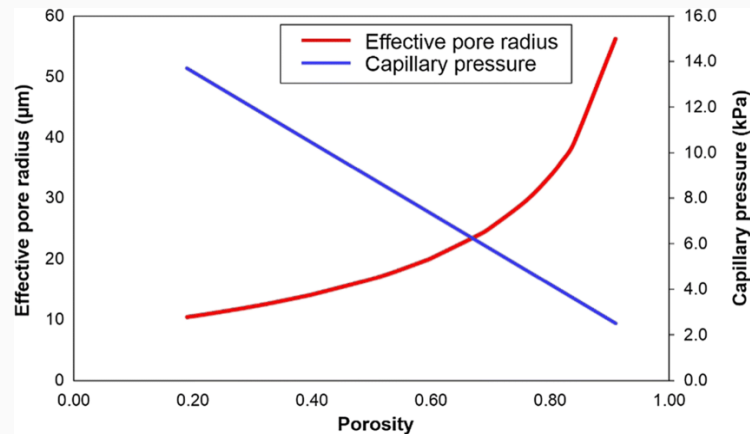


Dry-Out Limit and Design Tradeoffs



Key observations:

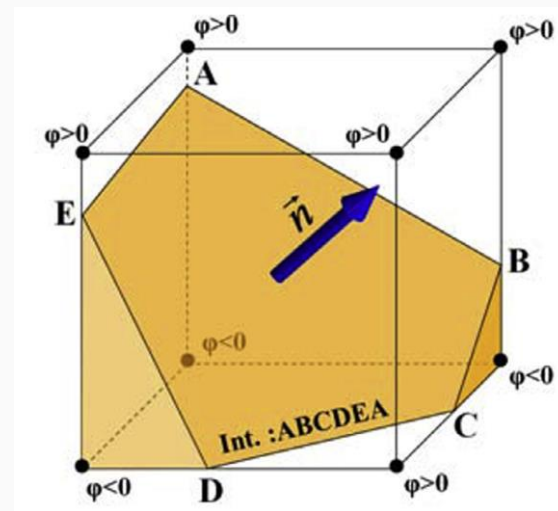
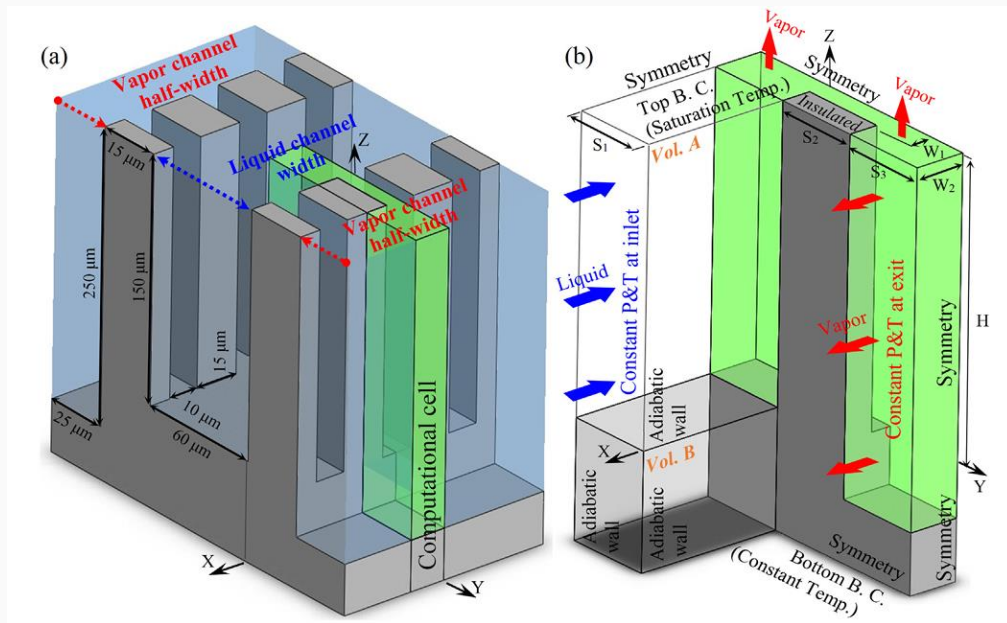
- Smaller spacing increases capillary pressure
- Larger spacing improves permeability
- Optimal geometry balances both effects



High capillary pressure $\longleftrightarrow$ High permeability

Multiphysics Modeling Framework

Numerical simulations for full capture of flow and heat mechanisms:



Resolving Thin-Film Evaporation Physics

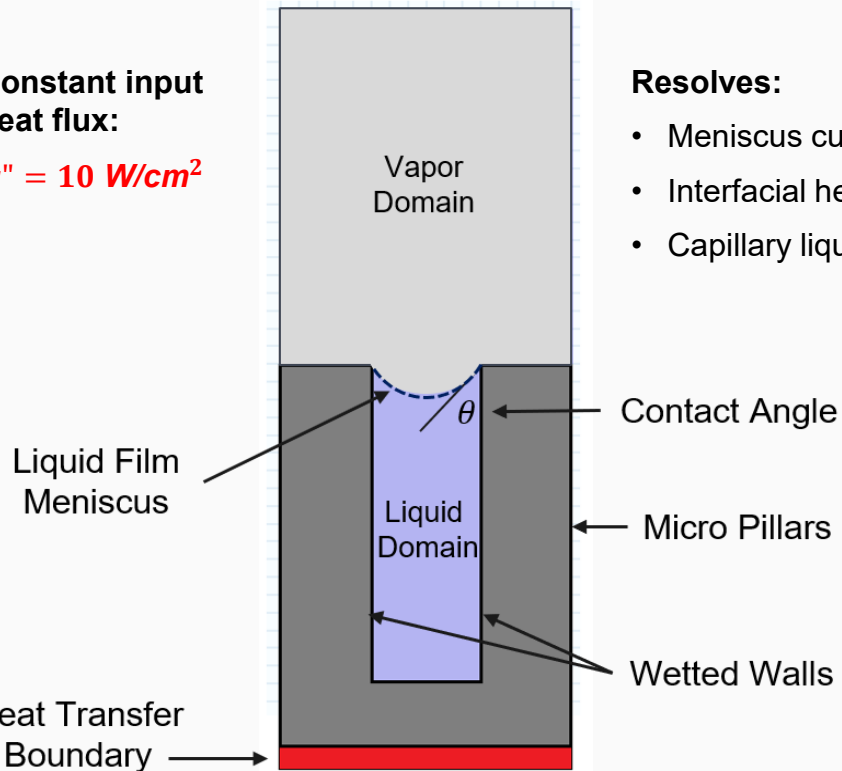
2D Unit Cell:

Constant input heat flux:

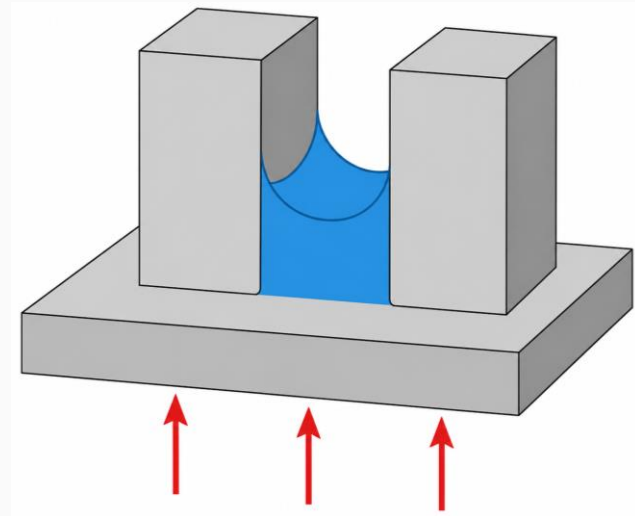
$$q'' = 10 \text{ W/cm}^2$$

Resolves:

- Meniscus curvature
- Interfacial heat transfer
- Capillary liquid transport



3D Representation:



Captures pressure difference based on capillary flow and viscous effects to visualize wicking liquid advancement

Thin-Film Evaporation Governs Performance

Why Film Formation Controls 3DHI Thermal Limits:

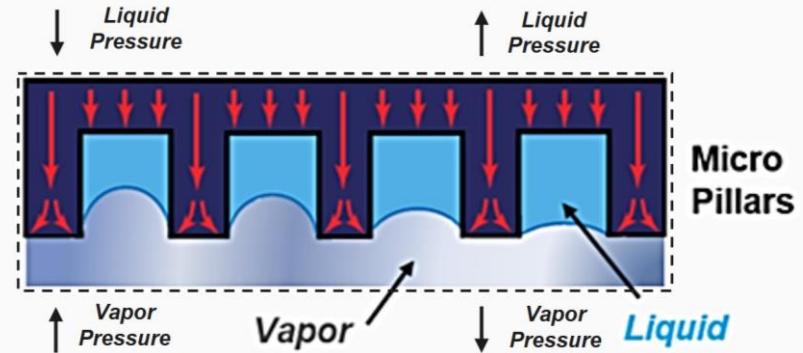
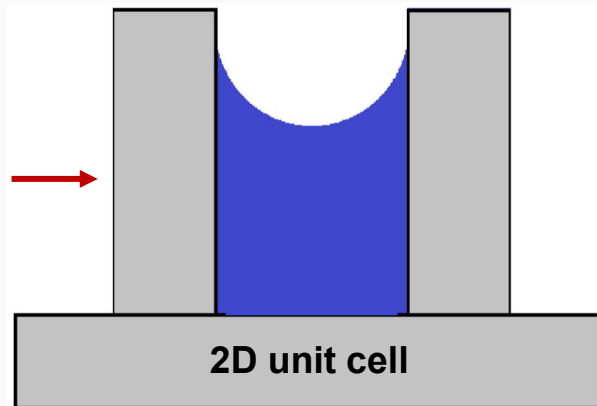
Vapor chamber functions:

- Stable thin-film evaporation
- Sustained capillary liquid supply

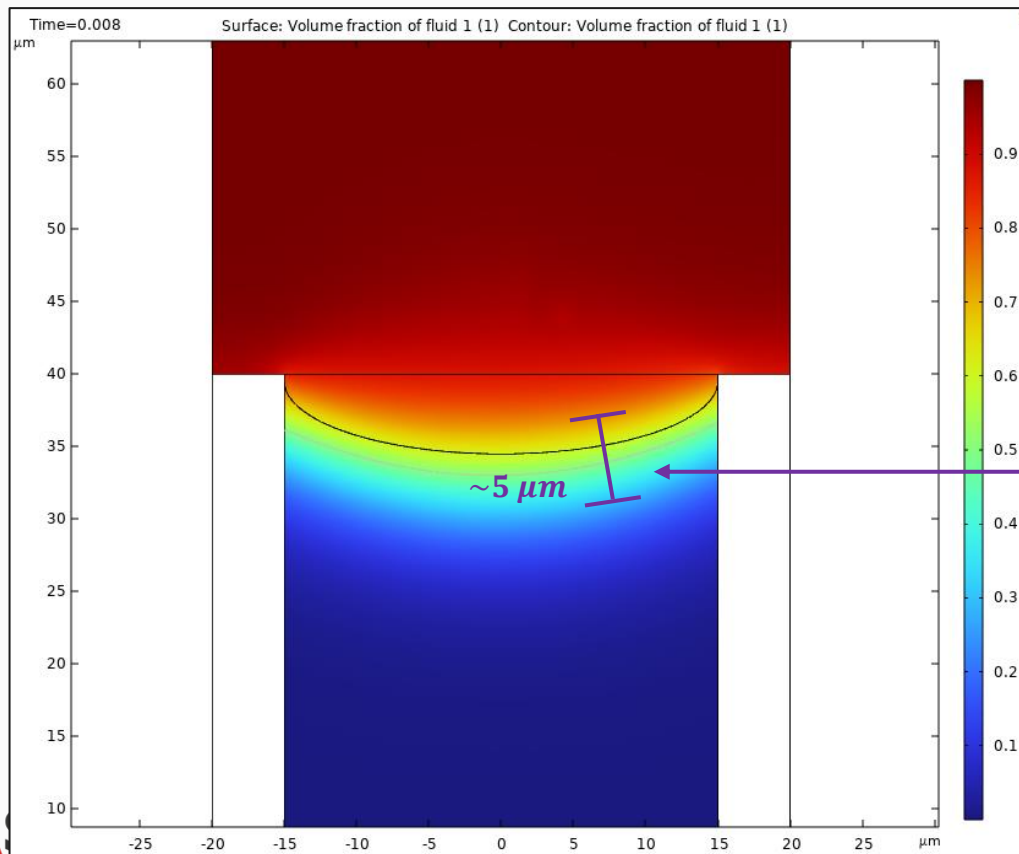
Failure mode:

- Liquid film dry-out
- Capillary limit
- Vapor choking

The performance of the entire device depends on what happens in this 30 μm gap between two pillars



Meniscus Formation



Boundary Layer Curvature

- **Capillary formation:** Stable interface
- **Wetting-controlled curvature:** Boundary layer thins toward the evaporation zone
- **No dry out events:** Capillary flow sufficient to sustain evaporation

Most heat transfer occurs within a micron-scale region near the contact line.

Capillary forces naturally establish a stable evaporating interface.



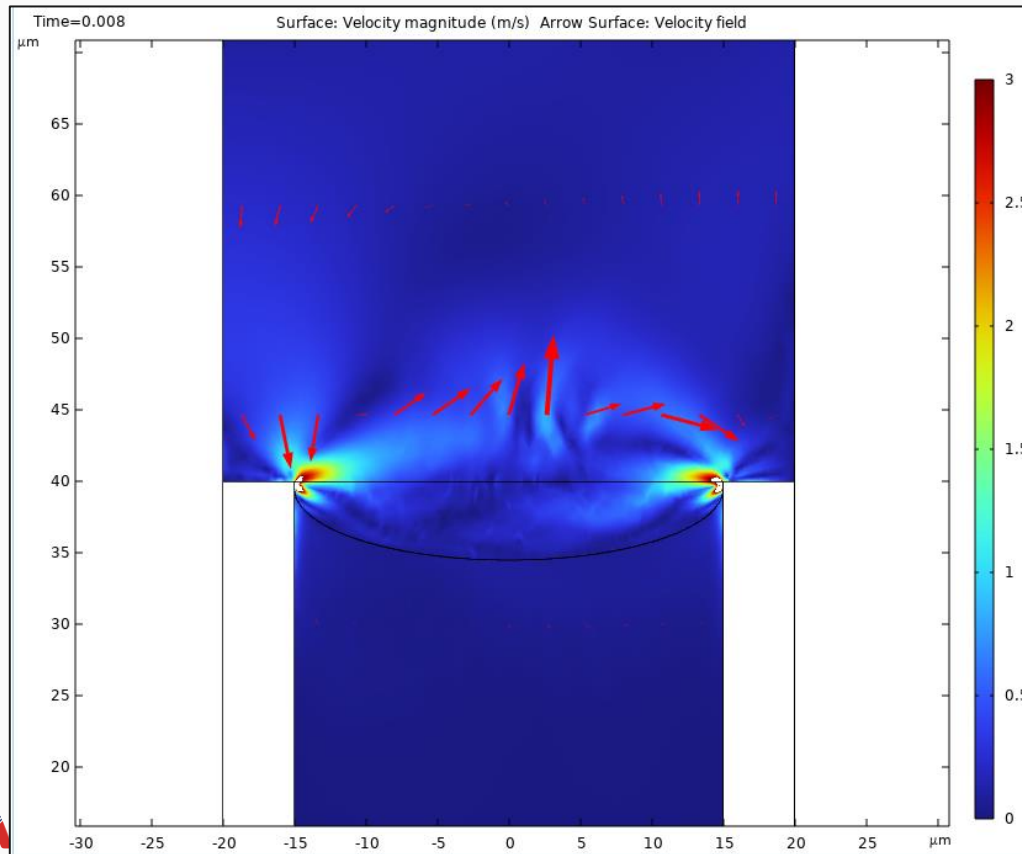
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Liquid Replenishment



Velocity Field

- Exceptionally low velocity (<3 m/s): beneficial and expected
- Increased velocity in wicking corners
- Continued capillary supply

Although velocities are relatively small, they are sufficient because liquid consumption occurs only within the thin-film region.

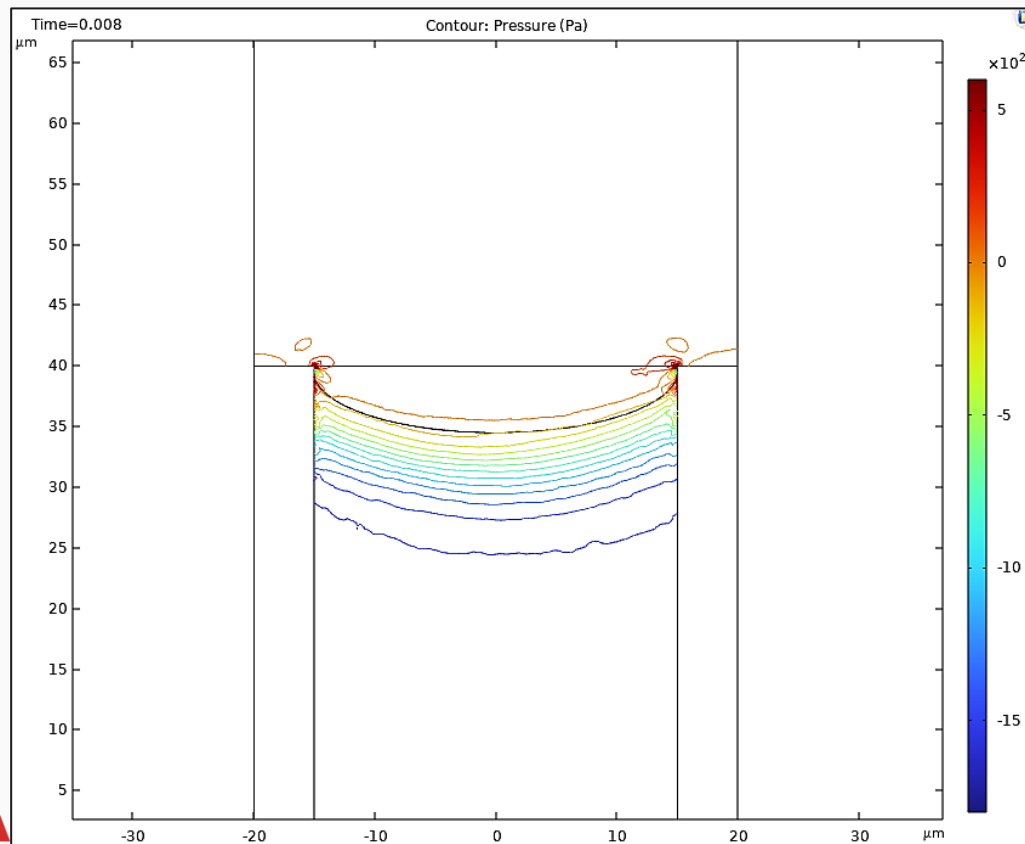


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Pressure Distribution



Pressure field balance

- Pressure variation follows meniscus curvature nearly exclusively (showing actual pressure balance between fluids)
- Small variation near pillar corners

Interface curvature generates the pressure gradient that drives liquid replenishment.



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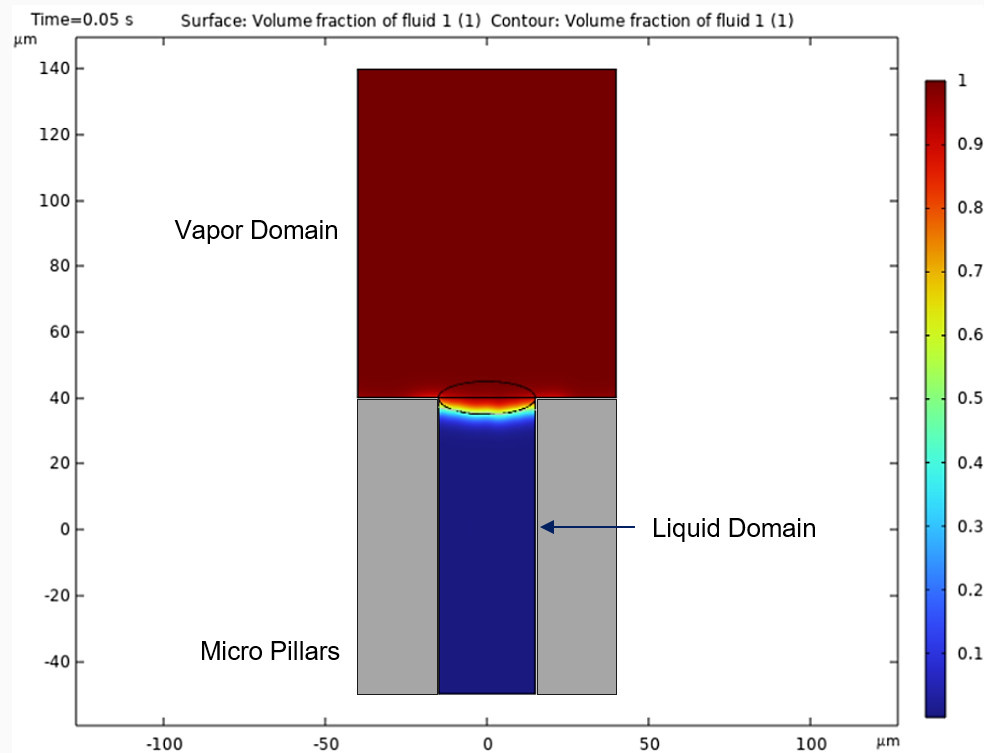
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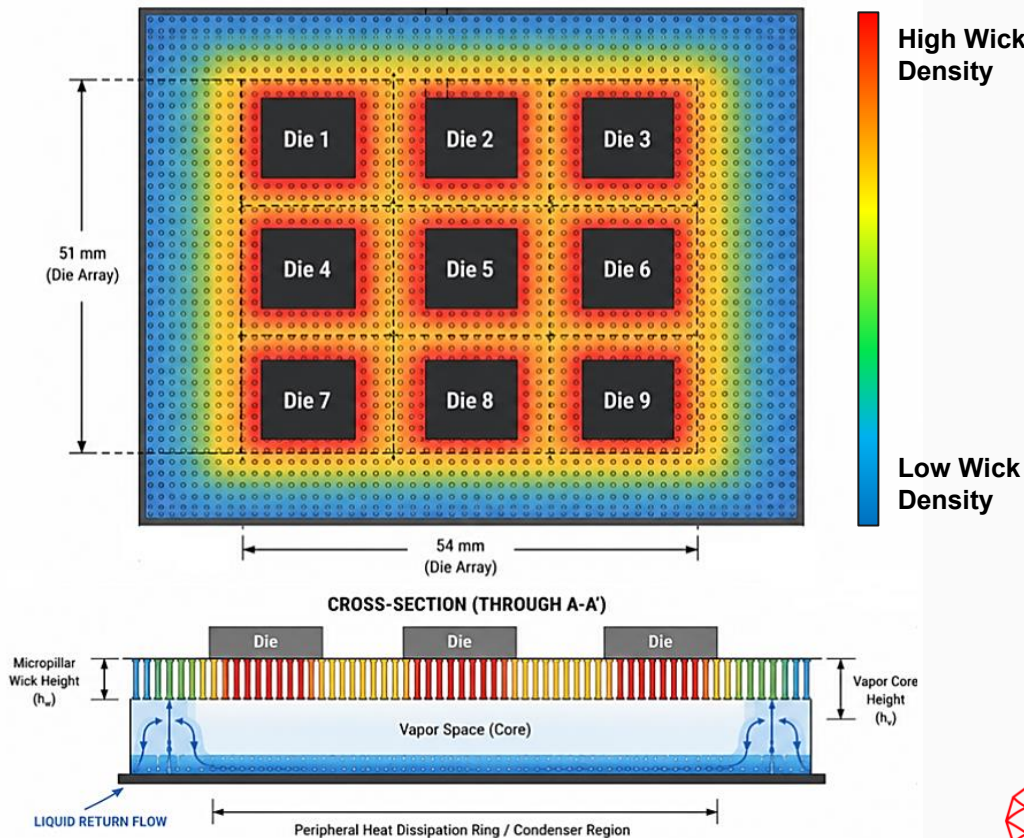
Key Modeling Insights

1. Stable meniscus formation was achieved
2. Capillary transport can sustain liquid replenishment
3. Thin-film evaporation governs hotspot cooling

These insights directly inform thermal interposer design.



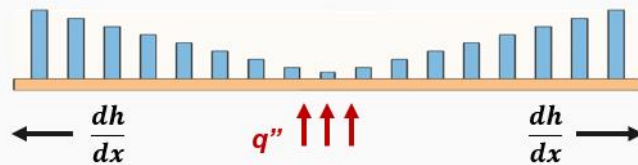
Design Pathways for Hotspot Mitigation



Innovative Upgrades

- Localized high-density wick regions beneath hotspots
- Spatially varying wick architectures across the package
- Geometry optimization for capillary transport and dry-out resistance

Micro Pillar Height Gradient:



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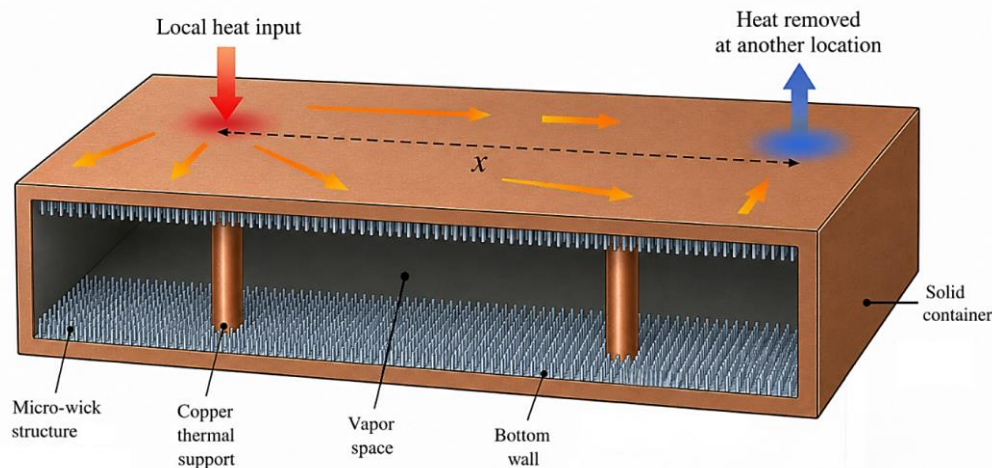


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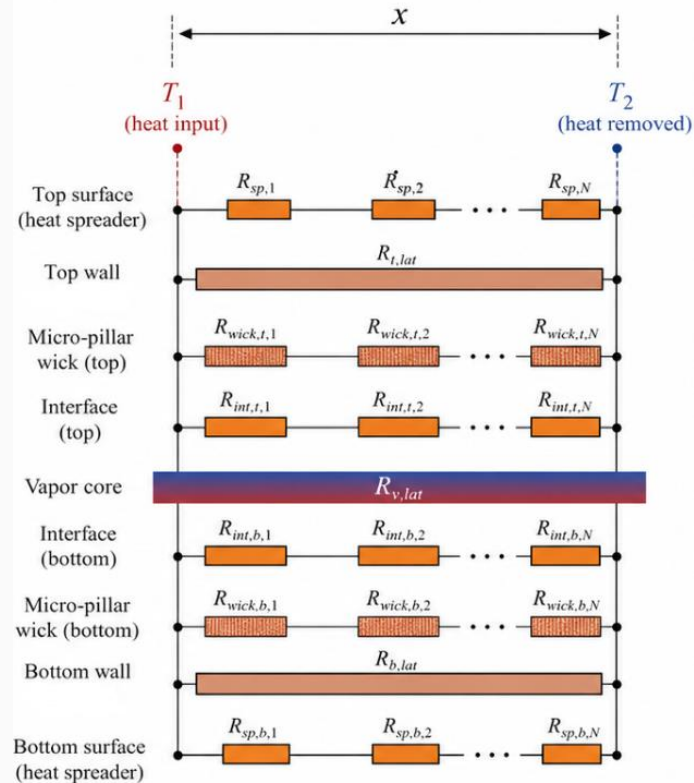


Solving the Temperature Gradient

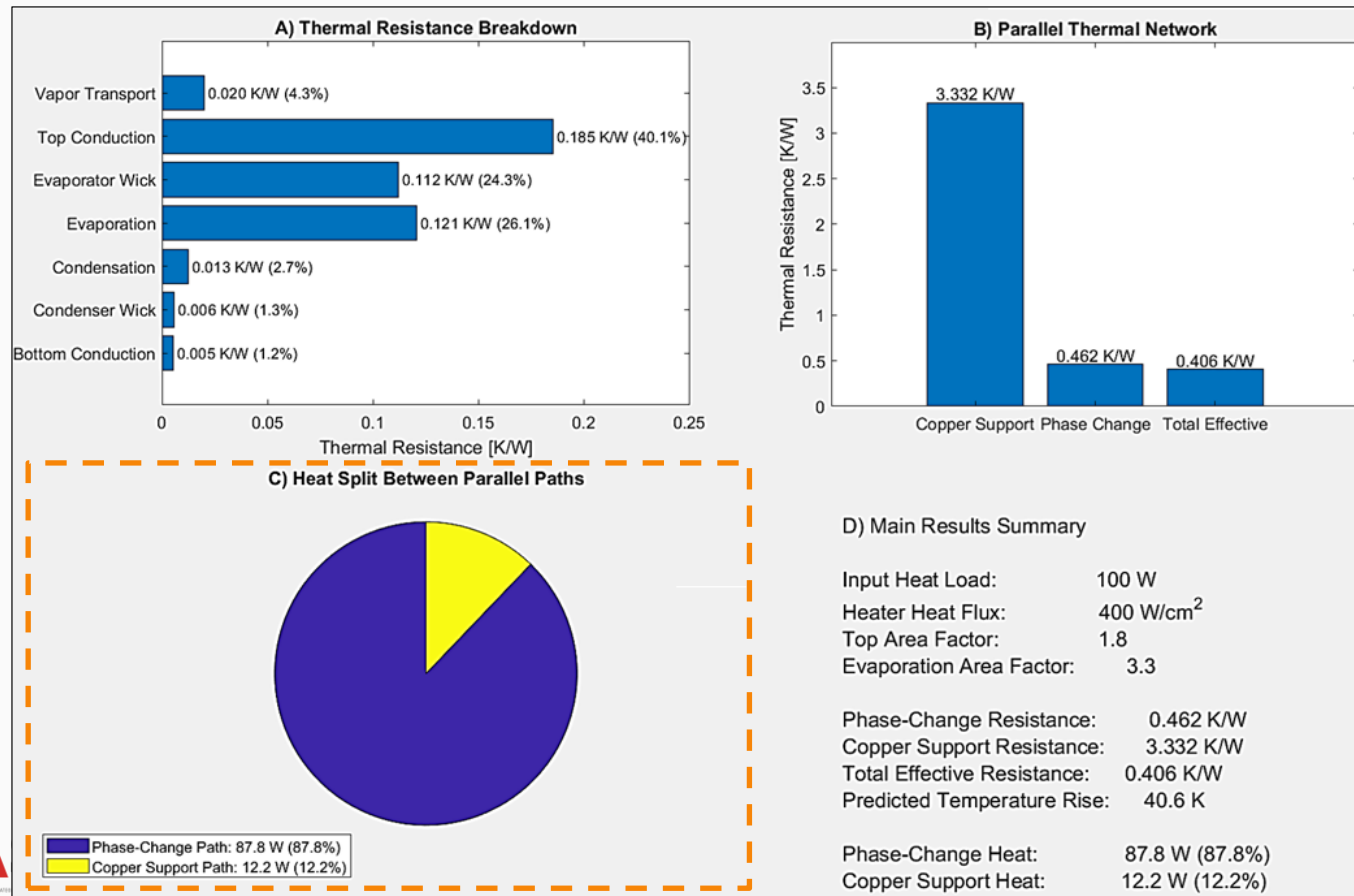
Heat Source → Vertical conduction → Evaporation →
Vapor transport → Condensation



A resistance-based framework identifies the dominant thermal bottlenecks within the interposer



Refined Thermal Resistance Network



Key Findings:

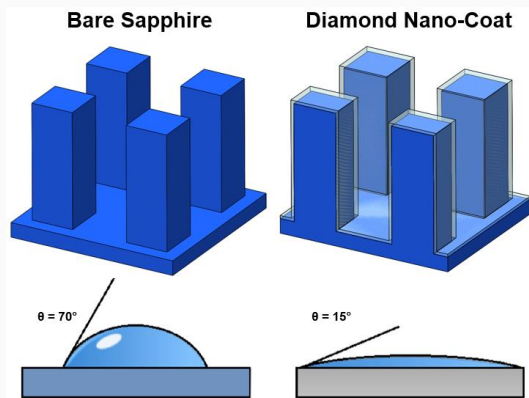
1. Hotspot spreading resistance dominates overall thermal performance.
2. Vapor transport losses are comparatively small.

Increasing the evaporator access area produces the largest temperature reduction.

Design Guidance for Future Interposers

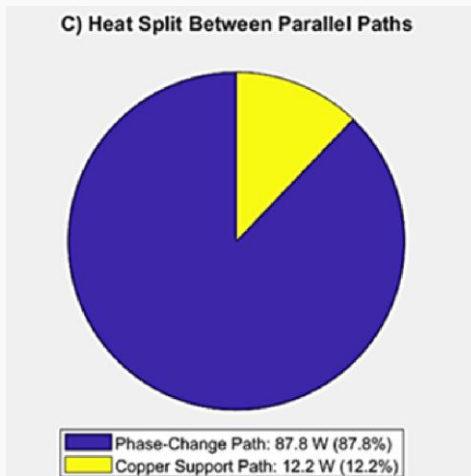
Diamond Coating

Improves thermal access to the evaporation interface.



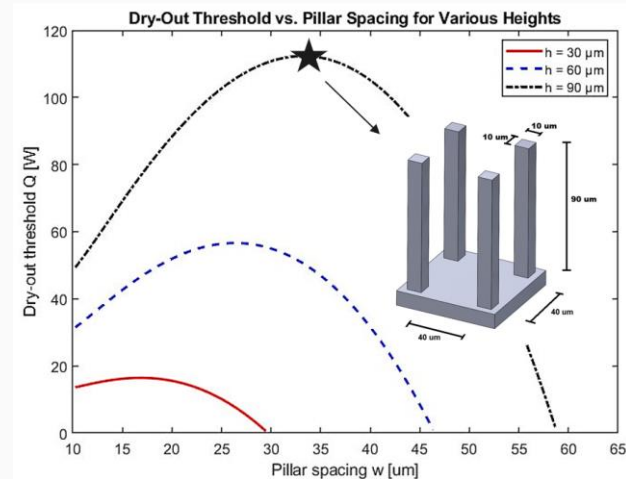
Thin-Film Evaporation

Controls hotspot cooling effectiveness.



Capillary architecture

Determines sustainable operating limits.



Impact on 3DHI Packaging

Thermal Performance:

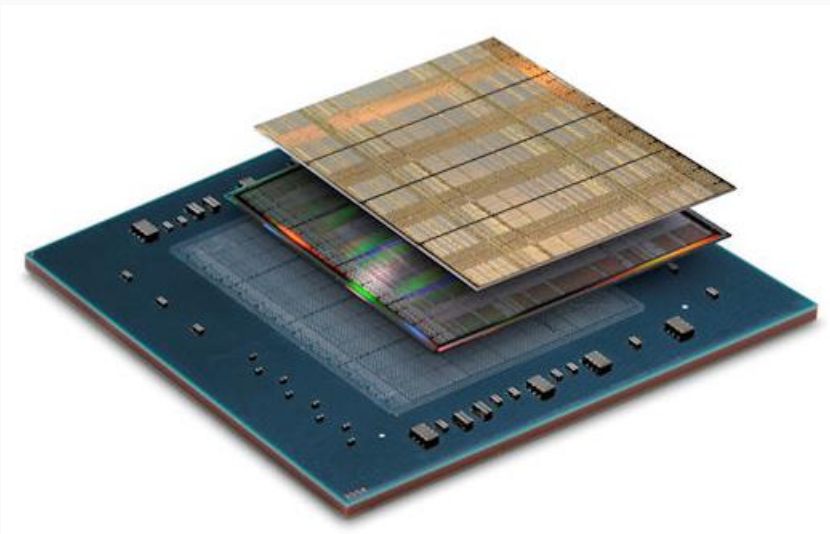
- Hotspot mitigation
- Higher sustainable heat flux

Package Integration:

- Embedded cooling within the interposer
- No external pumping architecture

Scalability:

- Compatible with advanced 3DHI platforms
- Manufacturable through laser processing



Enables higher-power operation within a fixed package footprint.

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Thank You!

Questions?



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