Transient Thermal Simulation for 3D ICs with Liquid Cooling and Through Silicon Vias

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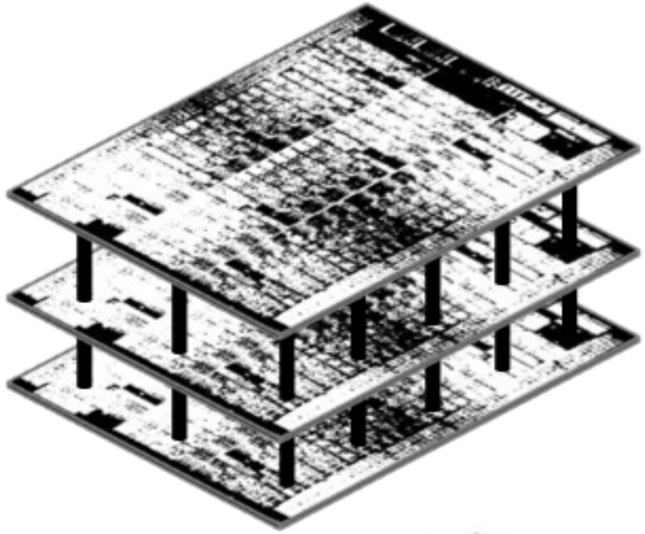
POLYTECHNIQUE MONTRÉAL
LE GÉNIE EN PREMIÈRE CLASSE

3D Many Core Platforms

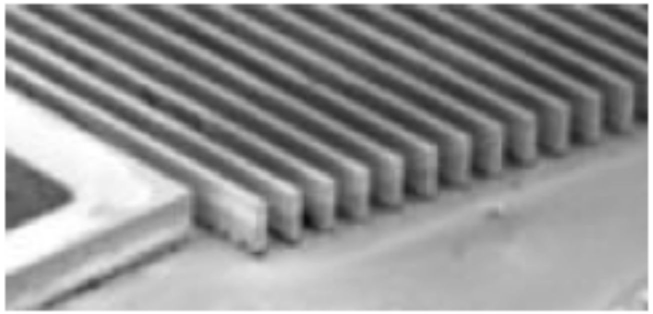
- Benefits of 3D Architectures
  - Reduced latency
  - Higher throughput
  - More compact chips
- Thermal Issues
  - Increased power dissipation
  - Poor heat dissipation
  - Conventional heat sinks obsolete



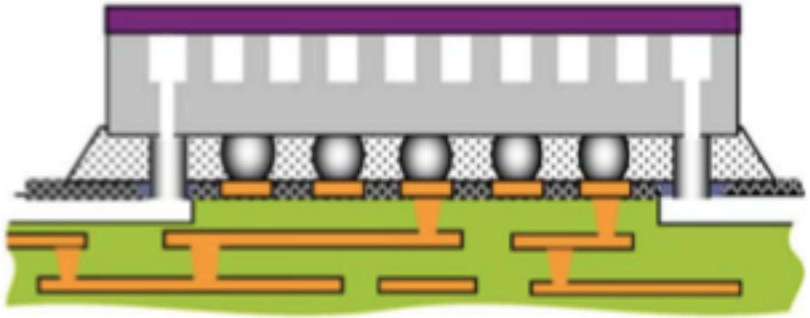
⇒ Advanced Cooling Solutions Needed

Liquid-Cooled 3D ICs

- Liquid Cooling
  - Microchannels etched at the backside of the die
  - Heat removed by the liquid circulating in the microchannel



Source: Yu *et al.*, 2010

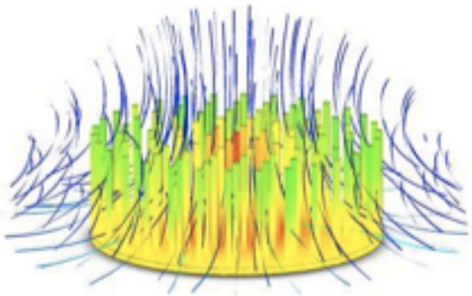


Source: Dang *et al.*, 2010

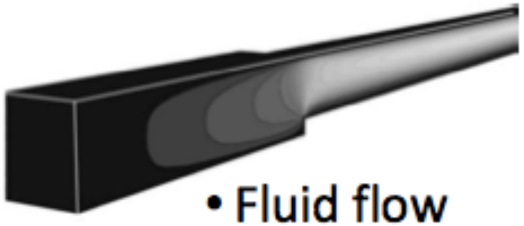
- Efficient but complex ➔ Thermal simulations needed
  - To develop dynamic thermal management policies
  - To ensure thermal reliability
  - To optimize the placement and the cooling system

Challenges

- Multiphysics simulation

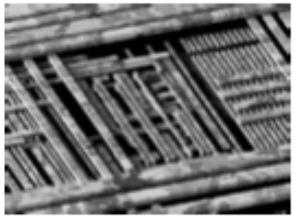


• Natural convection

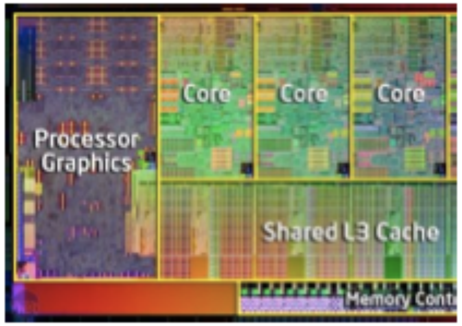


• Fluid flow

- Scaling



• Wire level

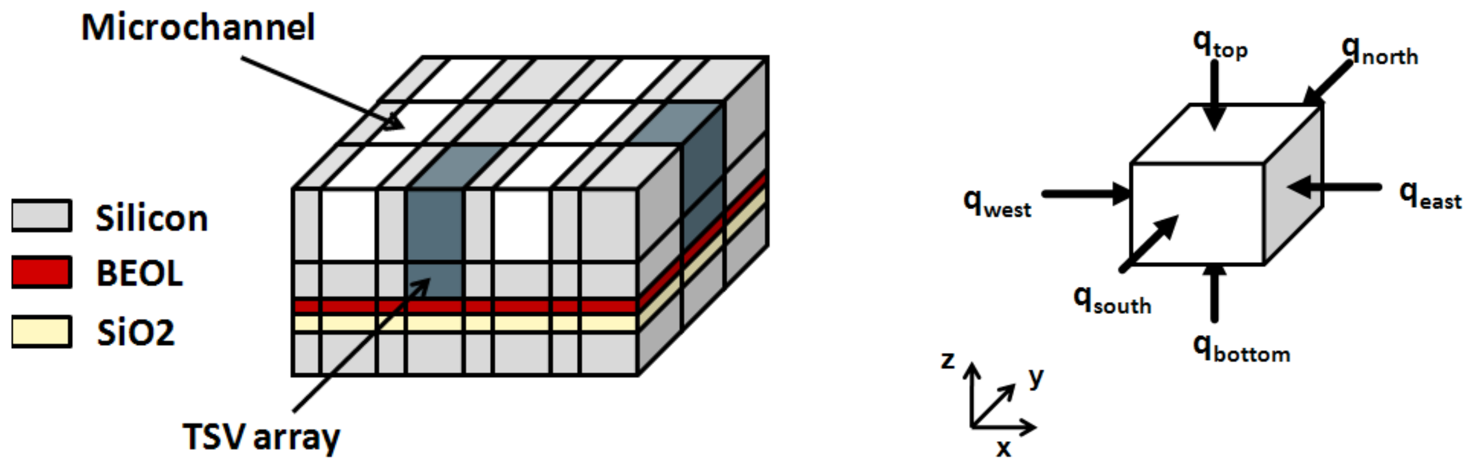


• Die level

• Package level

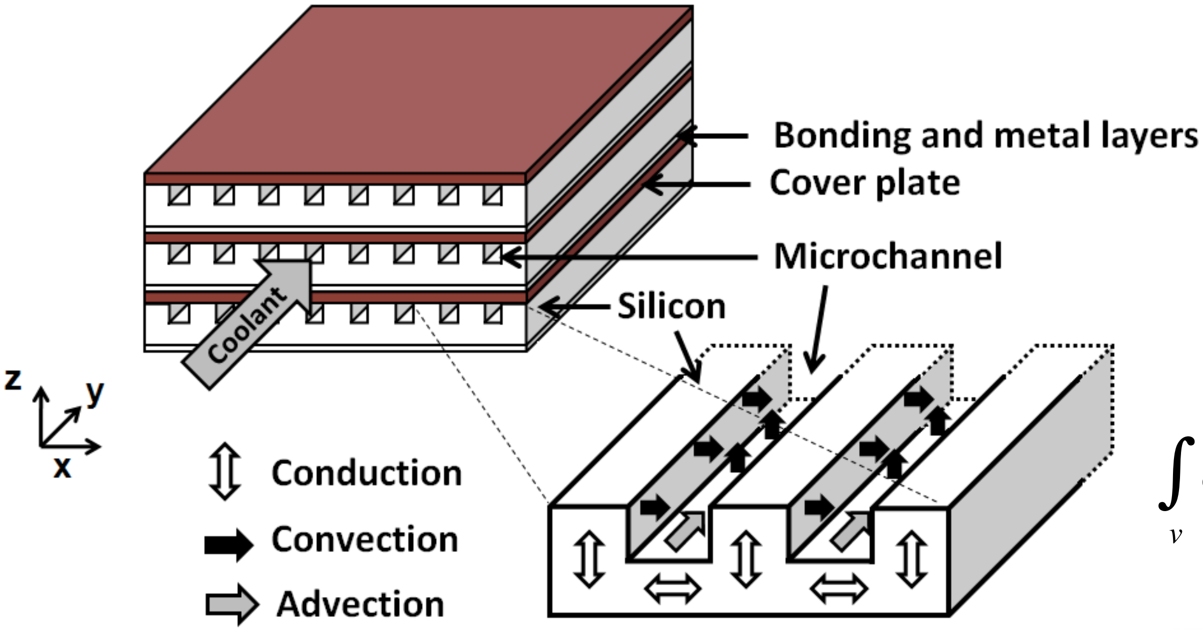
- Limitations of existing methods
  - Analytical → for simple problems
  - Numerical → high computation cost
- Simulators drawbacks
  - Long simulation time
  - Low accuracy
  - High memory usage

Compact Thermal Modeling for 3D ICs with Liquid-Cooling



- Based on the Finite Difference Method
- The circuit is discretized into small cubic cells – thermal cells
- Important number of thermal cells for realistic circuits (10^5 - 10^6 cells for one circuit)
- Complex problems to solve

Heat Transfers in 3D ICs with Liquid-Cooling



Heat Equation

$$\int_v c_v \frac{\delta T}{\delta t} dv = \int_S \vec{q} \cdot d\vec{s} + \int_v P_{vol} dv$$

Conduction $\vec{q}_{cd} = -k\Delta T$

Convection $\vec{q}_{cv} = h(T_{wall} - T_{liquid})\vec{n}_{wall}$

Advection $\vec{q}_{ad} = \int_s c_v T \vec{u}\, d\vec{s}$

Existing Solutions for 3D Ics Thermal Modeling

Author	Analysis	Solver	Complexity	Implementation
Kim	Steady state	Successive Under Relaxation	O(N)	CPU
Mizunuma	Steady state	Gauss-Seidel	O(N)	CPU
Feng	Steady state	Conjugate Gradient	O(N)	GPGPU
Sridhar	Transient	Backward Euler	$O(N^{1.5})$	CPU
Fourmigue	Transient	Operator Splitting	O(N)	CPU
Liu	Transient	GMRES	O(NM)	GPGPU
Vincenzi	Transient	Neural Metwork	$O(N^{x})$ *	GPGPU

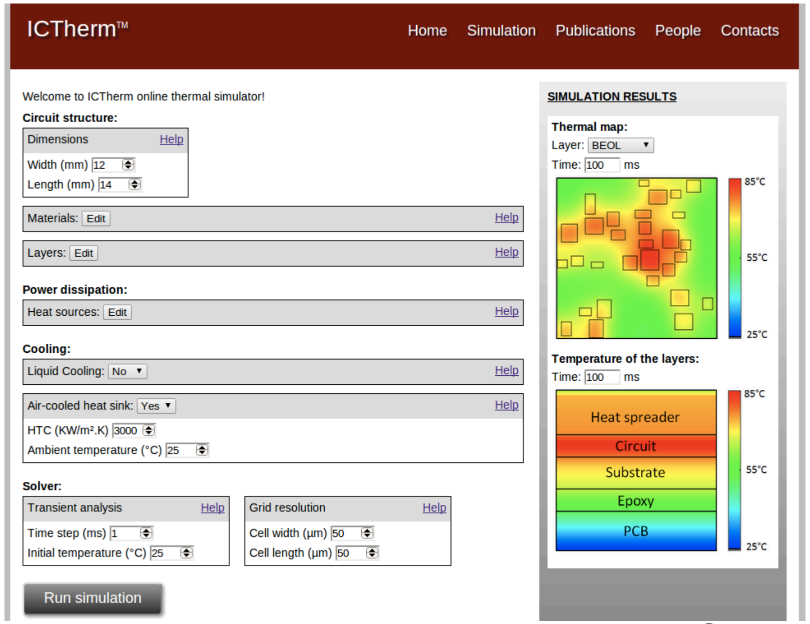
N – problem size

M – number of iterations

* $1 < x < 2$ depending on the chosen accuracy

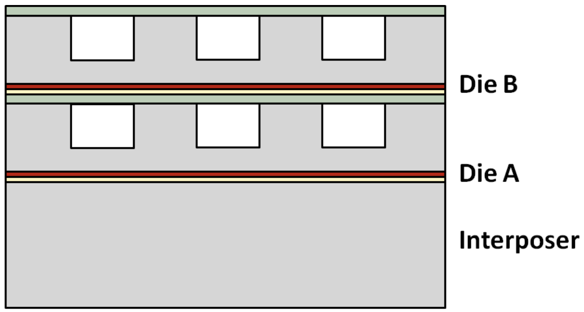
DYA Thermal Model

- Solver based on **D'Ya**konov finite difference method
  - Second order accurate in time
  - Unconditionally stable
  - Linear-time complexity
- Implemented in ICTherm tool



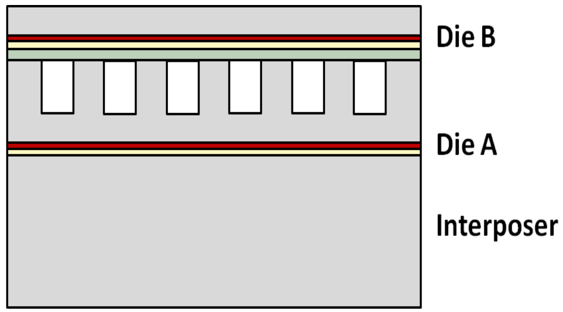
DYA Evaluation

Test Stack 1



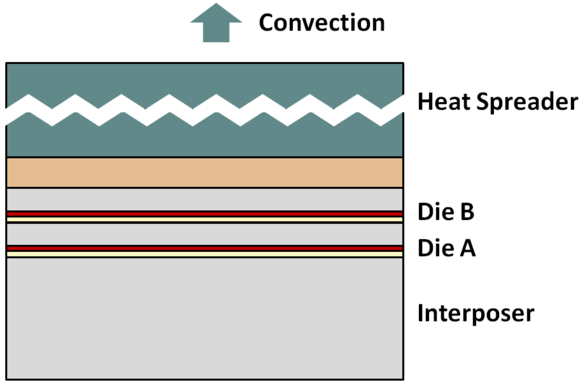
Microchannels	
Height (µm)	70
Width (µm)	70
Spacing (µm)	100
Coolant	Water
HTC (W/m^{2}C)	2.72e4
Veocity (m/sec)	1.4

Test Stack 2



Microchannels	
Height (µm)	70
Width (µm)	50
Spacing (µm)	50
Coolant	Water
HTC (W/m^{2}C)	3.84e4
Veocity (m/sec)	0.8

Test Stack 3

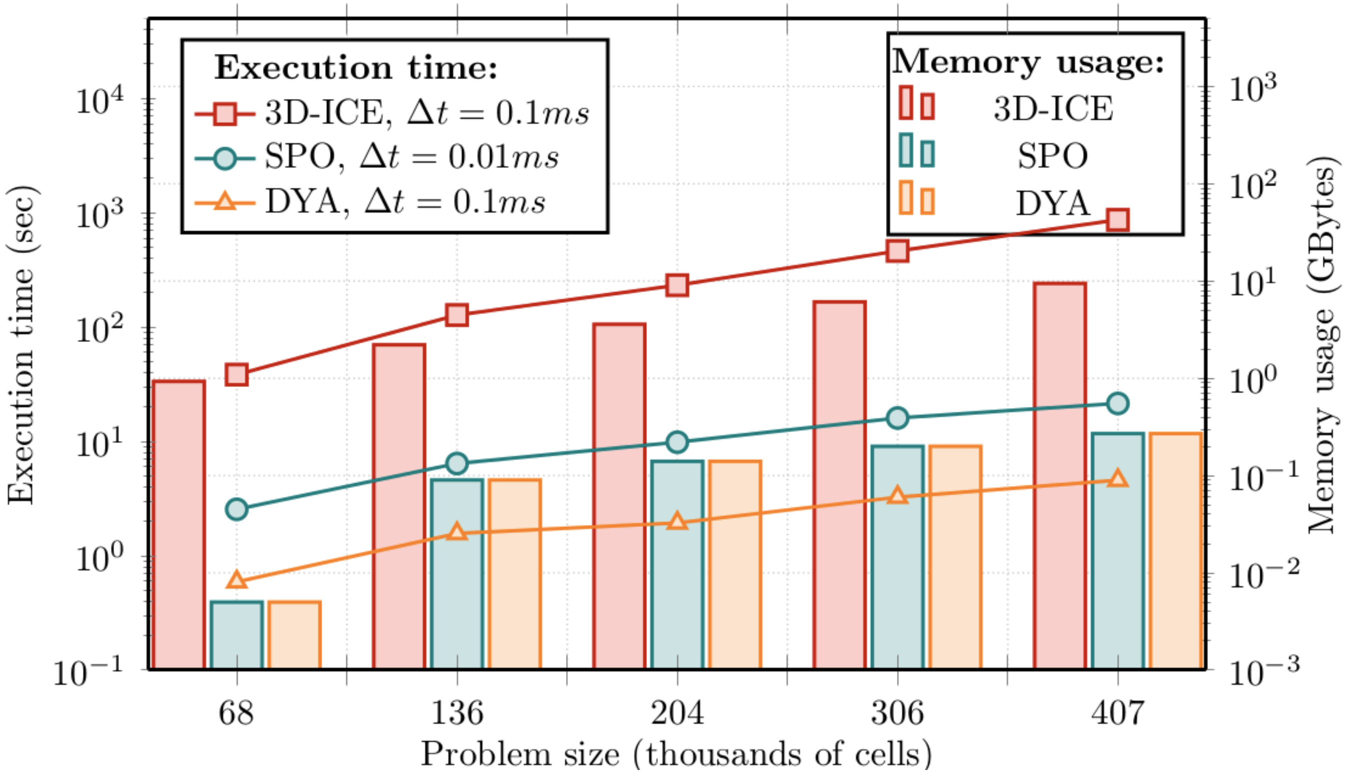


Heat Spreader	
Material	AlSiC
Thickness (µm)	1000
Thermal Paste	
Material	TIM
Thickness (µm)	50
Convection	
HTC (W/m^{2}C)	3.3e3

Accuracy Evaluation

- Simulation based on DYA
  - Five time more accurate than simulation based on Operator Splitting Method (used in SPO tool)
    - For the same simulation time
  - Remains close to the accuracy provided by simulation based on Backward Euler Method (used in 3D-ICE tool)

Performance Evaluation



- ➢ DYA is 5-6 times faster than SPO
- ➢ DYA outperforms 3D-ICE of two orders of magnitude

Summary

- Thermal analysis is imperative for SoC design
- EDA tools for thermal aware design are essential
- New thermal model for 3D ICs
  - The best accuracy – speedup – memory usage trade-off in state-of-the-art
  - Allows modeling realistic 3D ICs