



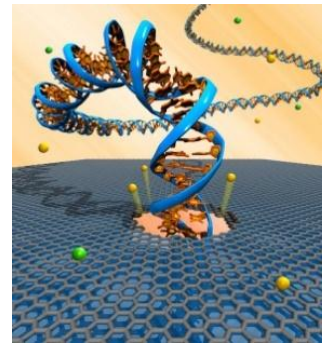
**NANYANG**  
TECHNOLOGICAL  
UNIVERSITY

# Thermal Simulator of 3D-IC with Modeling of Anisotropic TSV Conductance and Microchannel Entrance Effects

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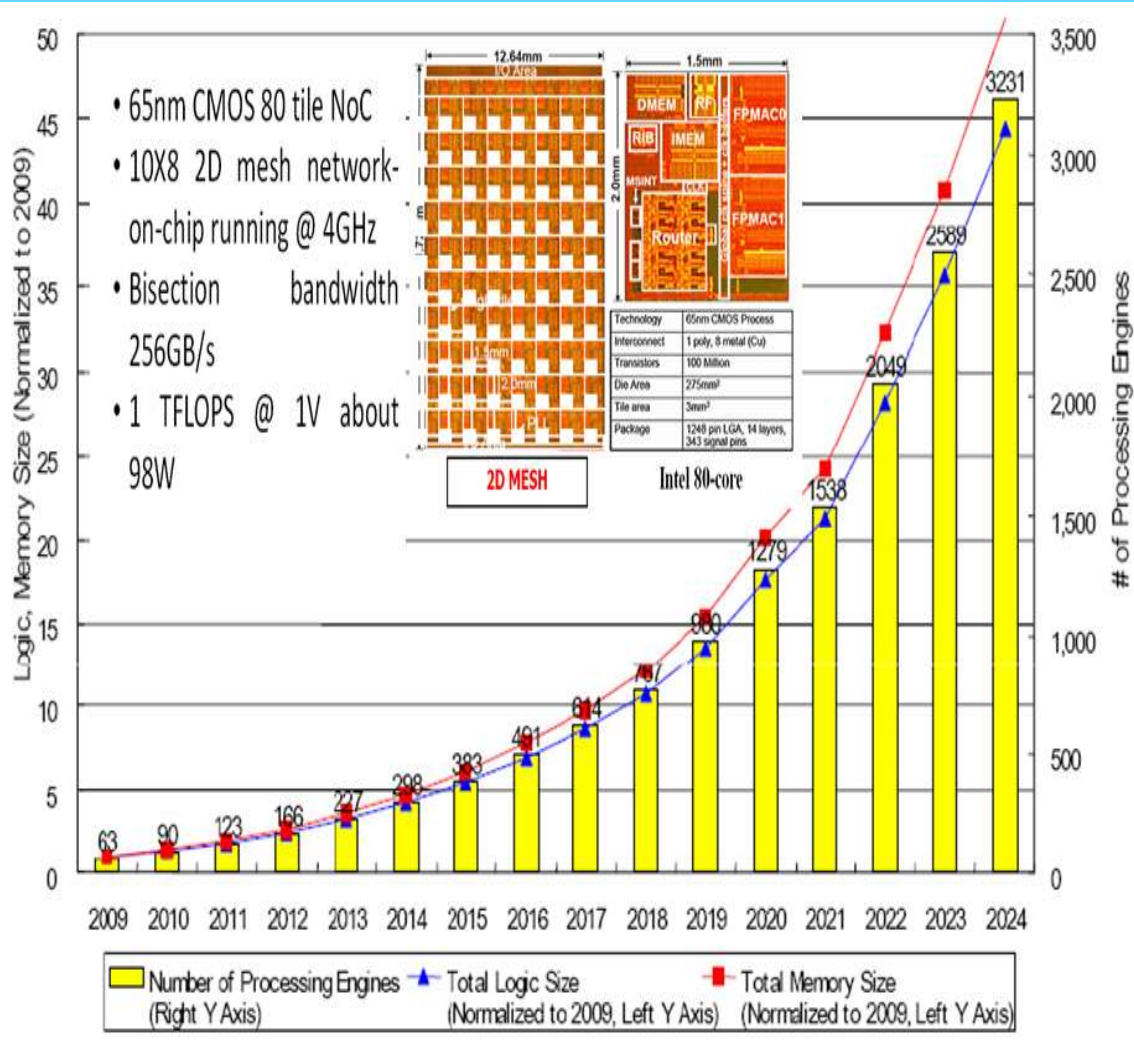
# Big Data Era: from Teta ( $10^{15}$ ) to Exa-scale ( $10^{18}$ )

- **'Moore's' Law:** transistors double every 18 months
- **90% of today's data was created in the last 2 years**
  - Facebook: 20TB/day compressed; NYSE: 1TB/day
- **Many more:** web logs, energy consumptions, medical records, etc.



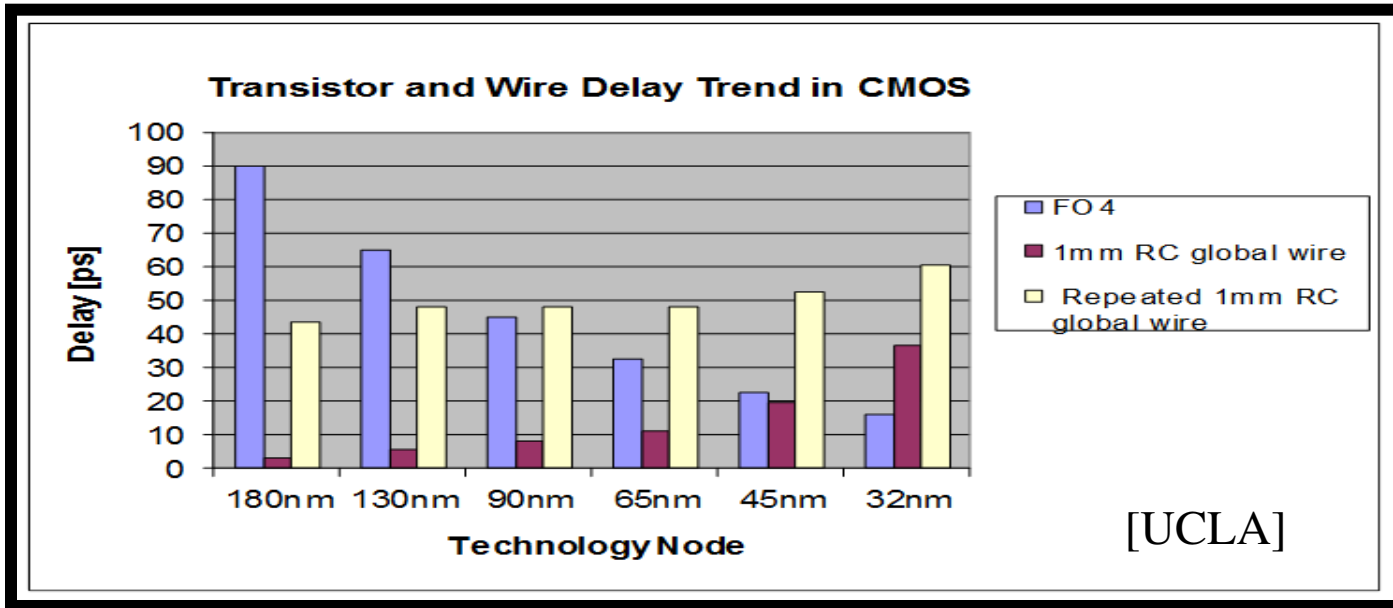
**It is not just a software game!**

# Cloud On-chip Server for Big-data Processing



- More cores are integrated on the same chip for parallelism
- Cores are scaled down in size but with maintained frequency (2~4GHz) due to power density
- Performance is limited by communication efficiency between cores and memories

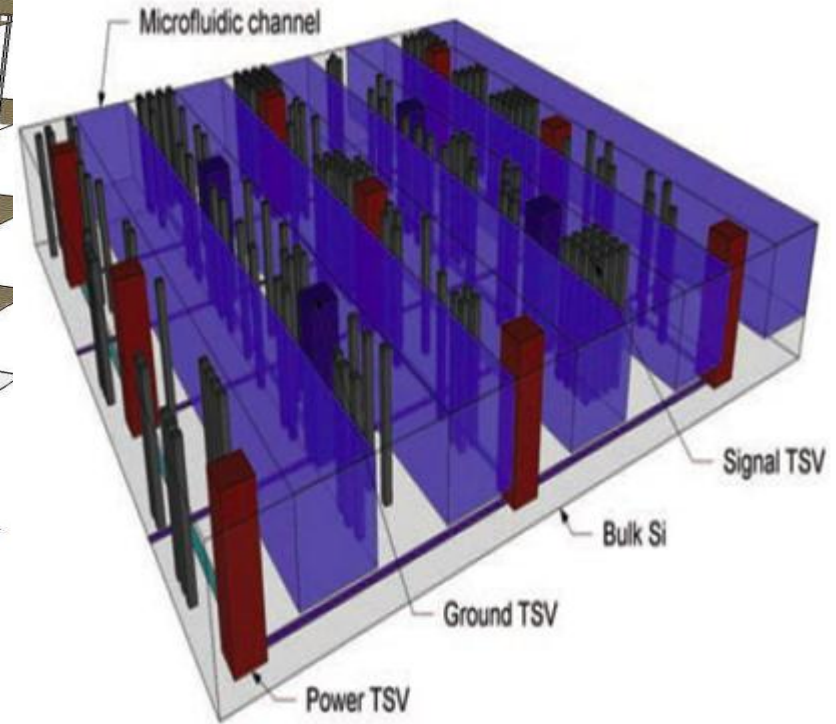
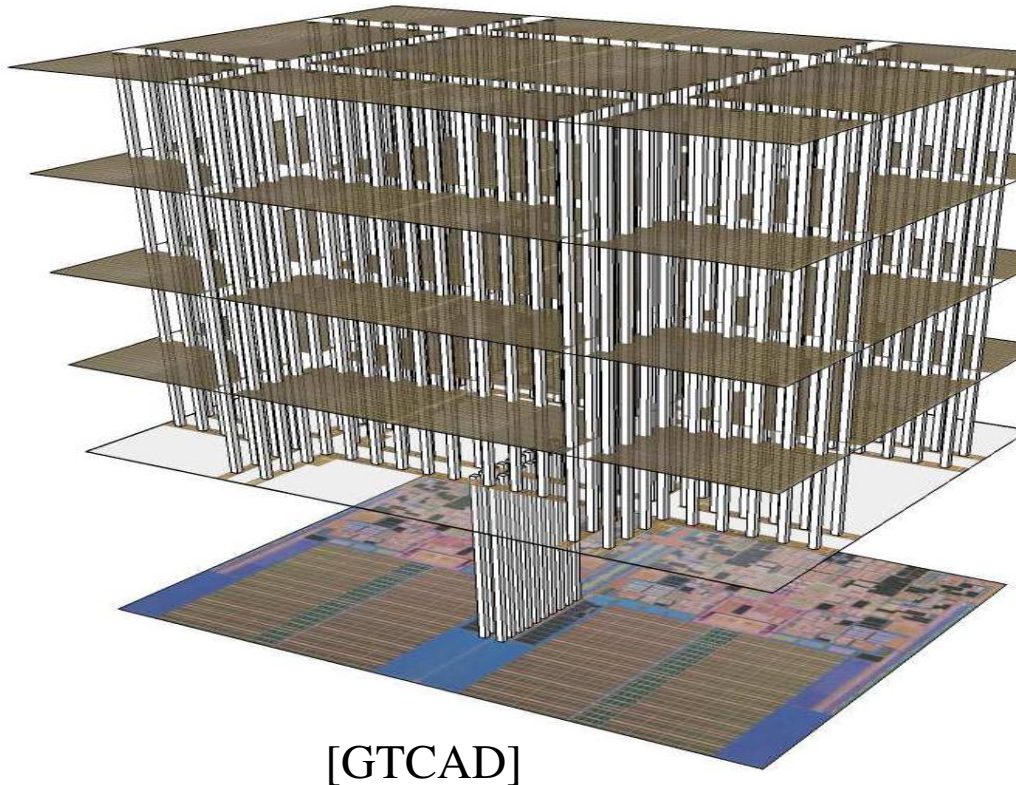
# 2D Interconnect Scaling Slow-down



- **Wire (L) latency not scaling down**
  - Voltage signal charging/discharging of cap: RC-limited ( $\sim L^2$ ) and reduced with repeater ( $\sim L$ )
  - Scaling reduces delay of gate but not wire: latency is large across chip
- **Energy consumption not scaling down**
  - Supply voltage not scalable due to leakage



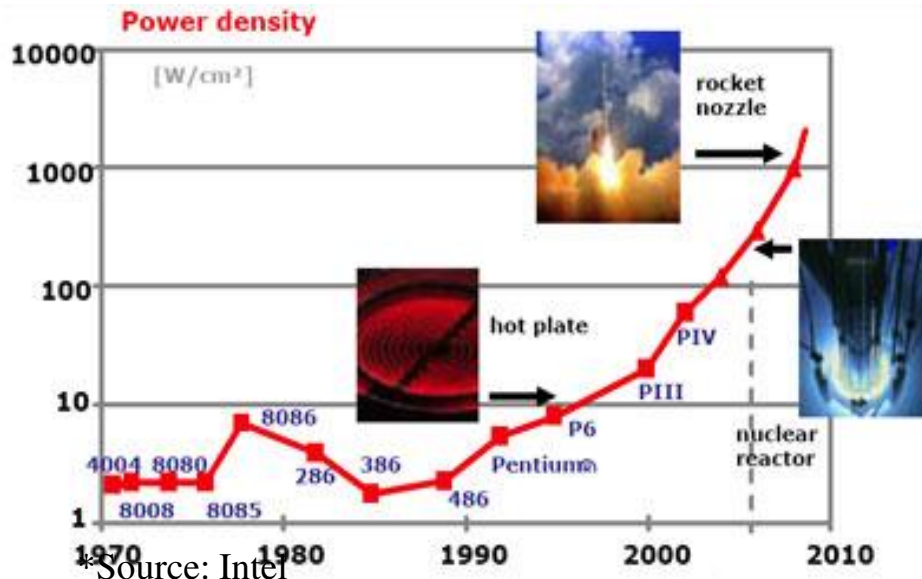
# How can 3D Integration Help?



- Vertical structured I/Os for memory-logic interconnection with significant interconnect latency reduction
- Heterogeneous integration for emerging technologies with more knobs of power and thermal management

# Thermal Challenges in 3D

- **High Power Density**



- **Long heat transfer path for circuit layers that are far away from heatsink**

- **Thermal-aware Design and Novel Cooling Techniques**

- a). Power Control

- DVFS [Donald06]
- Load Scheduling and Balancing [Coskun07]
- Thermal-aware Floorplan [Cong04]

- b). Cooling Control

- Thermal TSV Insertion [Kim09]
- Microfluidic Cooling [Dang05]

# Need of 3D Thermal Simulator

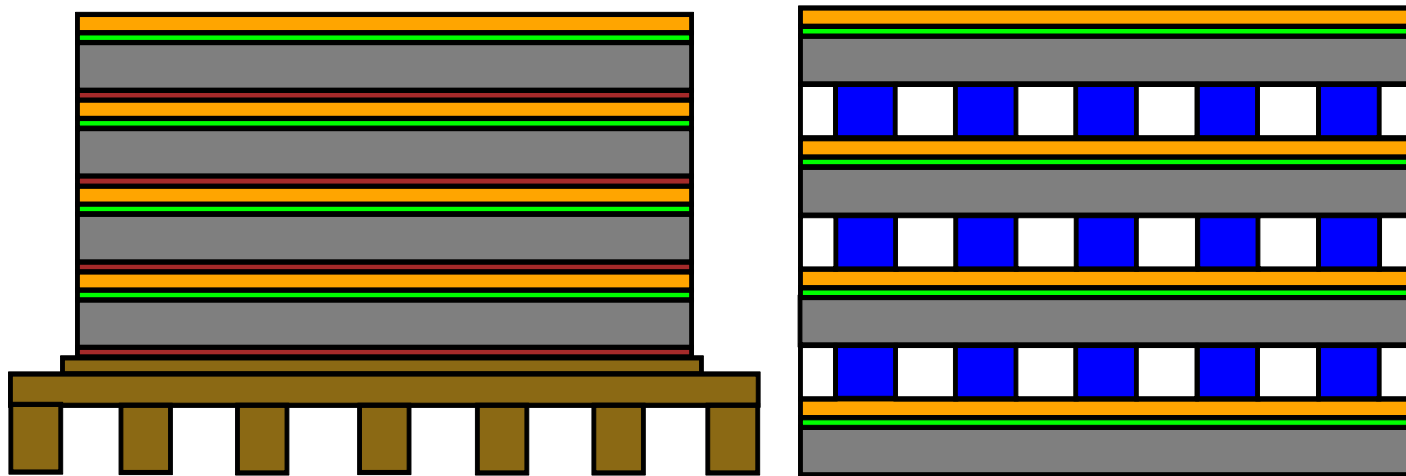
- A fast and accurate thermal simulator is needed for 3D thermal management
- Available Options:

Commercial Numerical Simulator	Available Open Source Simulator
General and accurate	Specific, moderately accurate
Long simulation time	Significant speedup
Subject to charges	Open source available
ANSYS, COMSOL	Hotspot, 3D-ICE

- Hotspot [Huang04]: lack of microfluidic cooling model.
- 3D-ICE [Sridhar10]: Ignorance of microchannel entrance effects
- Both Hotspot and 3D-ICE have not considered model specifically TSV anisotropic thermal effect

# Targeted Problem

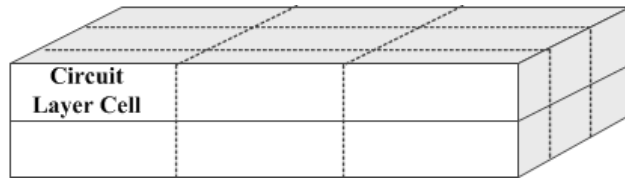
- Model both heat-sink-based air-cooling and microfluidic cooling
- Layer composition:
  - Back End of Lines (BEOL), Devices, and Bulk Sub-layers
- **TSV anisotropic effect and microchannel entrance effect**



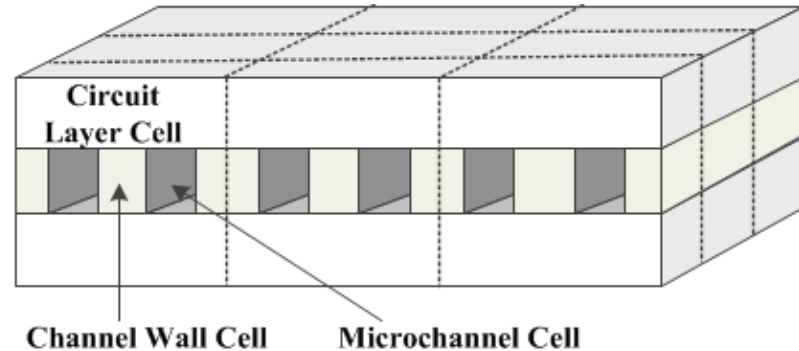
■ BEOL ■ Device ■ Bulk ■ TIM ■ Spreader and Heatsink □ Wall ■ Channel



# Modeling Methodology



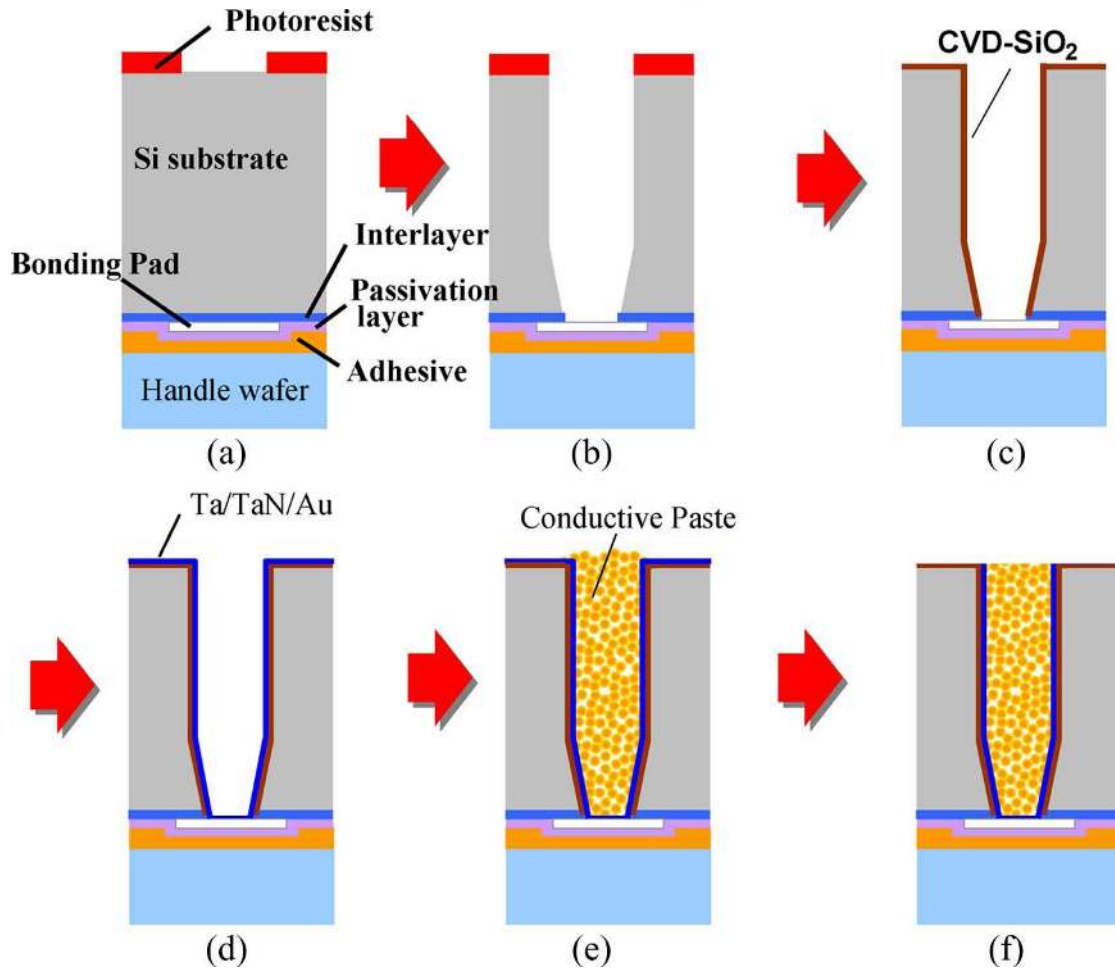
Heatsink-Cooled (Circuit Part Only)



Microfluidic-Cooled

- **Finite Element Analysis**
  - Divide 3D systems into grid cells
  - Obtain the thermal conductance between each grid cell
- **Steady State Analysis**
  - Setup thermal balanced equation for each cell
  - Solve system equations simultaneous for whole thermal profile

# TSV Device Fabrication



- Back side lithography;
- Deep Si-etch and SiO<sub>2</sub> RIE;
- SiO<sub>2</sub> deposition and RIE;
- Contact metal/barrier metal deposition;
- Paste printing;
- Contact and barrier metal removal.

- Typical Dimension:  $d_m$ : 5-20  $\mu\text{m}$ ;  $d_i$ :  $\sim 0.25 \mu\text{m}$
- Typical Thermal:  $k_{liner} = 30 \text{ W/(mK)}$ ;  $k_{metal} = 400 \text{ W/(mK)}$  for Si<sub>3</sub>N<sub>4</sub> liner and Copper fill

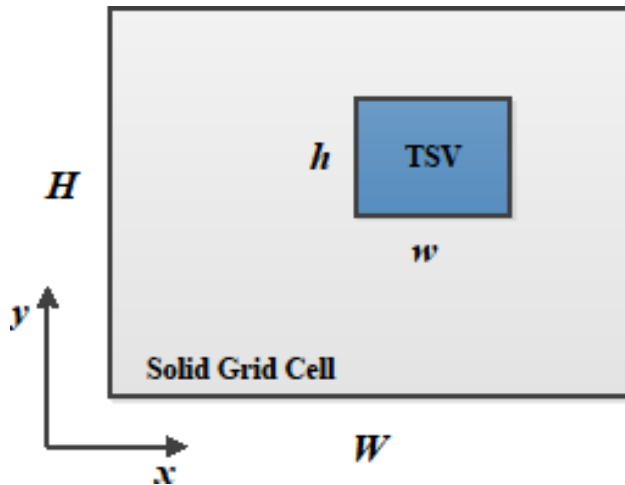
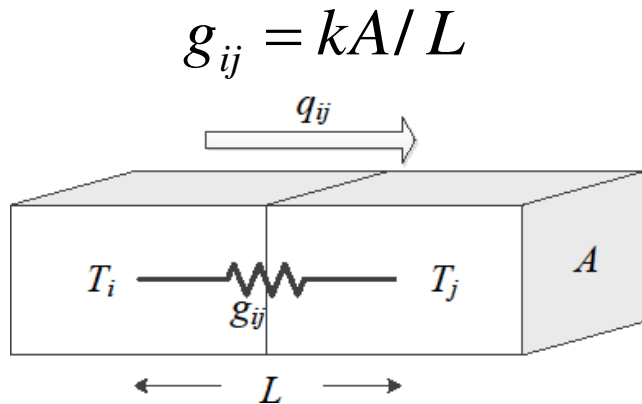
Source: [Motoyoshi09]

# Significance of TSV Anisotropic Effect

- **Metal TSV as filling material**
  - Good heat conductivity
- **Silicon oxide as liner**
  - Thermal insulator with poor heat conductivity
- **TSV Anisotropic Effect: different heat conduction properties along different direction**
  - Heat conductivity in 3D-IC depends on size and location
  - Simple model with averaged heat conductivity may over-estimate lateral conduction and fail to detect hotspots
  - Fine-grained anisotropic TSV modeling is needed

# Model of Anisotropic TSV Effect I

- Heat Conduction in Solid



- With TSV inserted

$$g_x = \left(1 + \frac{wh(\beta - 1)}{WH(1 + (1 - w/W)(\beta - 1))}\right) g_{x0}$$

$$g_y = \left(1 + \frac{wh(\beta - 1)}{WH(1 + (1 - h/zh)(\beta - 1))}\right) g_{y0}$$

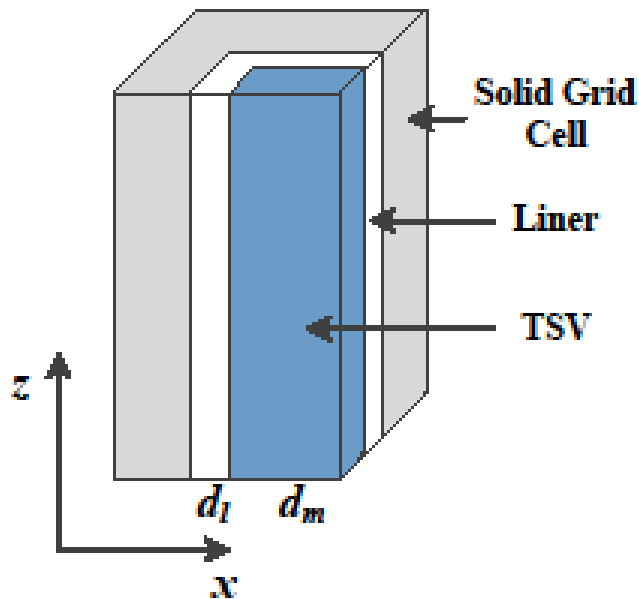
$$g_z = \left(1 + \frac{wh(\beta - 1)}{WH}\right) g_{z0}$$

$g_{x0}$ ,  $g_{y0}$  and  $g_{z0}$  : thermal conductance of grid cell without TSV

$\beta$ : ratio between thermal conductivity of TSV and grid cell ( $k_{TSV}/k_{cell}$ )

# Model of Anisotropic TSV Effect II

- **Equivalent thermal conductivity of TSV**
  - Differ in different direction
  - Liner tends to offset the high thermal conductivity in lateral direction, but have less influence along vertical direction



$$k_{TSV,xy} = \left(1 + \frac{d_m^2(\gamma - 1)}{(d_m + 2d_l)(d_m + 2d_l\gamma)}\right)k_{liner}$$

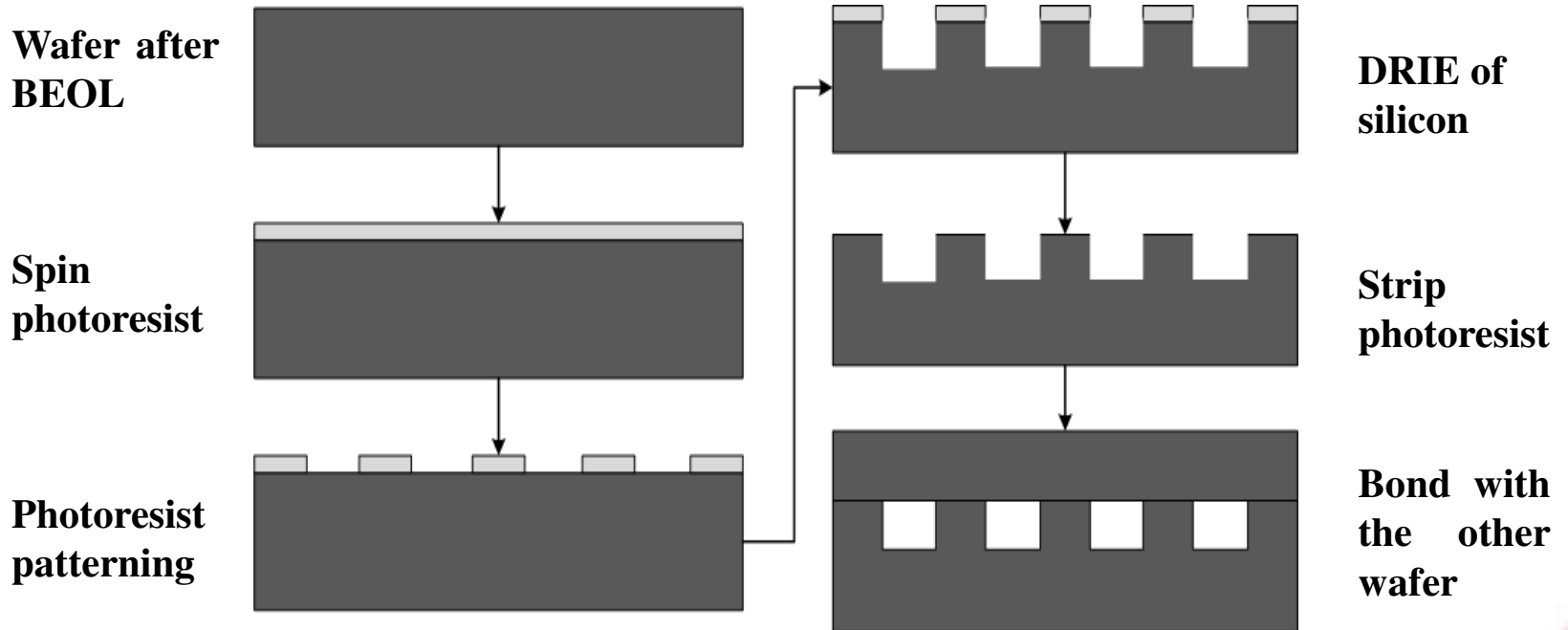
$$k_{TSV,z} = \left(1 + \frac{d_m^2(\gamma - 1)}{(d_m + 2d_l)^2}\right)k_{liner}$$

$$\gamma = k_{metal} / k_{liner}$$



# Microchannel Device Fabrication

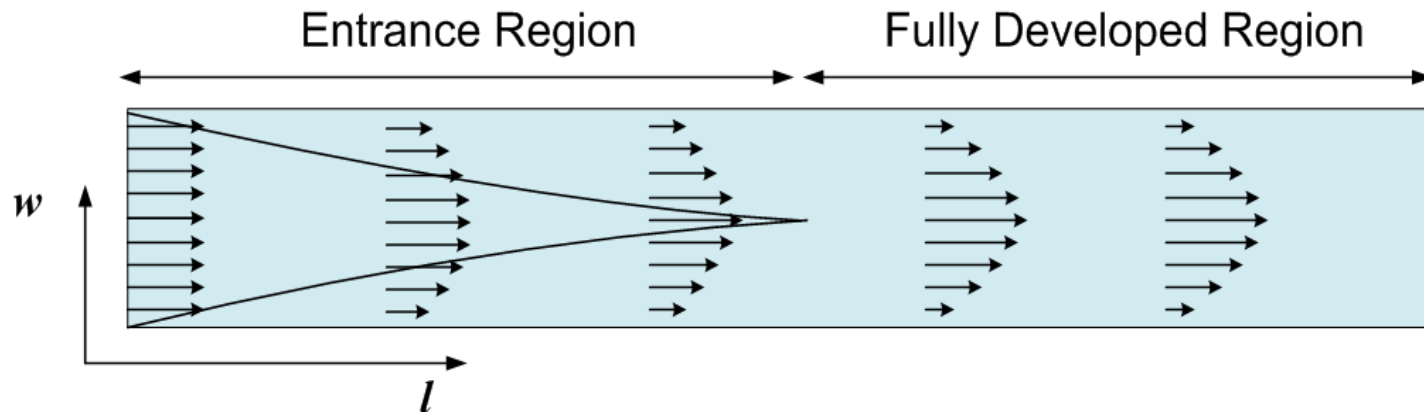
A direct etch and bond process for a 2-layer 3D-IC with microchannel



**Typical Microchannel Width:** 50-200  $\mu\text{m}$ ;  
**Typical Microchannel Height:** 50-200  $\mu\text{m}$ ;  
**Flow Speed:** < 2.5m/s;  
**Pressure Drop:** < 90 Kpa.

# Significance of Microchannel Entrance Effect

- **Entrance Effect:** better thermo-conductivity properties exhibited by laminar flow-fluid near inlet of microchannels due to its developing velocity profile
  - More effective thermal convection within entrance length
  - Ignorance of entrance effect will cause serious deviation of thermal profile

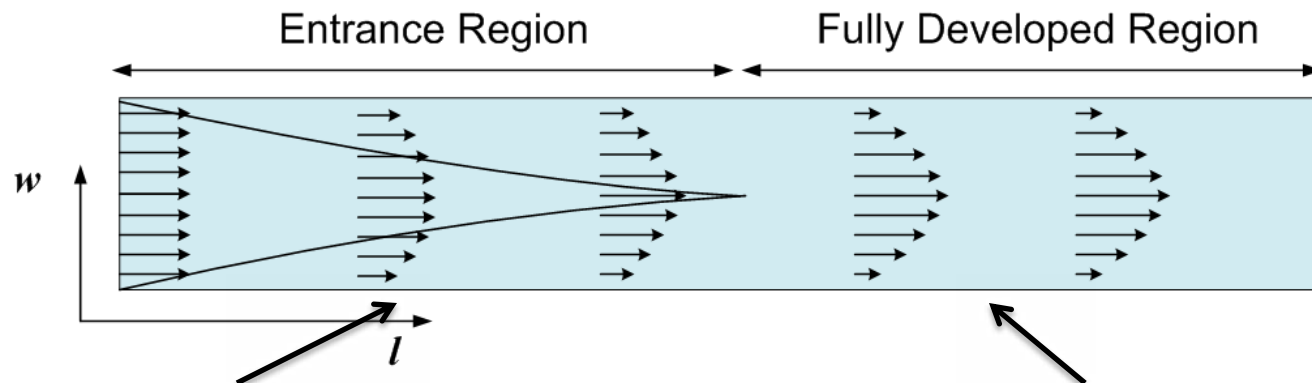


# Model of Microfluidic Entrance Effect I

- Convective conductance between channel wall and coolant is characterized by the heat transfer coefficient  $h$

$$g_{conv} = hA_{conv} \quad h = k_f Nu / D_H \quad D_H = 4A_{ch} / P_{ch}$$

- Nusselt number  $Nu$  needs to be formulated separately for the entrance region [Sedier36] and fully developed region [Peng96] to count for entrance effect

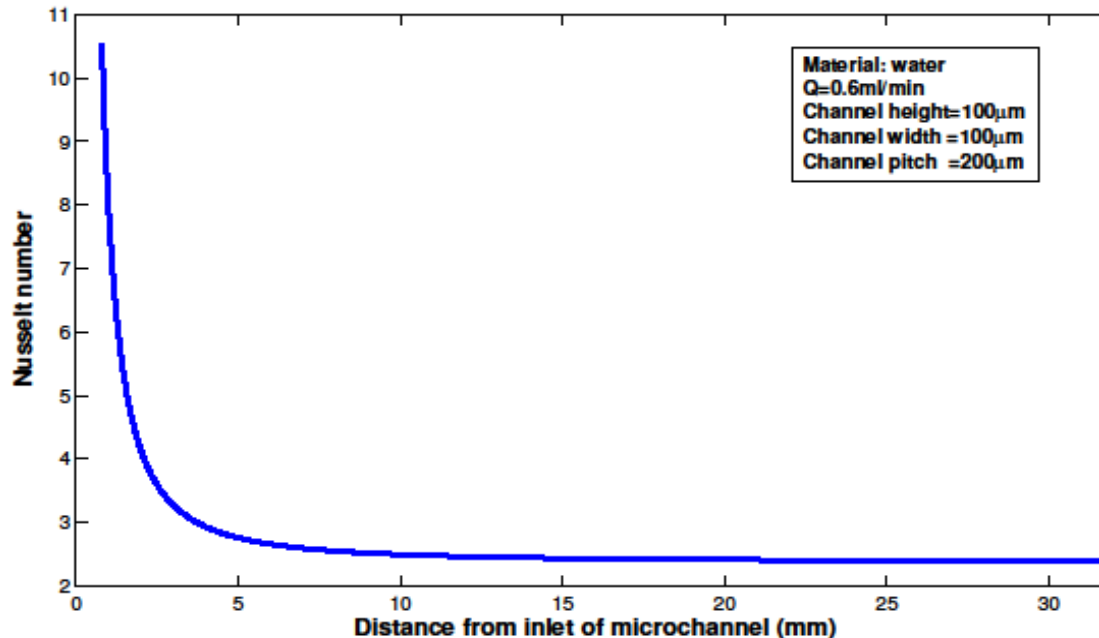


$$Nu_{st} = Nu_0 (\text{Re} \cdot \text{Pr})^{1/3} \left(\frac{D_H}{l}\right)^\eta \quad Nu_{pp} = 0.1165 \left(\frac{D_H}{\text{Pitch}}\right)^{0.81} \left(\frac{H_{ch}}{W_{ch}}\right)^{-0.79} \text{Re}^{0.62} \text{Pr}^{1/3}$$

$$Nu = Nu_{pp} + Nu_{st}$$

# Model of Microfluidic Entrance Effect II

- **Nusselt number considering entrance effect**
  - High heat-transfer coefficient near inlet area
  - Approach to a much lower constant value along flow direction
  - Ignorance of entrance effect results in a constant heat-transfer coefficient, and hence severe under-estimation of spatial thermal gradient



# Steady State Simulation under Thermal Balance

- **Thermal balance of every grid cell at steady state**

$$\sum (T_i - T_{i,adj}) \cdot g_{i,adj} = P_i$$

- **Heat transfers through microchannel cell by massive flow**

$$\sum_{j \in \{walls\}} g_{ch,i,j} (T_{ch,i} - T_j) = (T_{ch,i} - T_{ch,i-1}) Q C_V$$

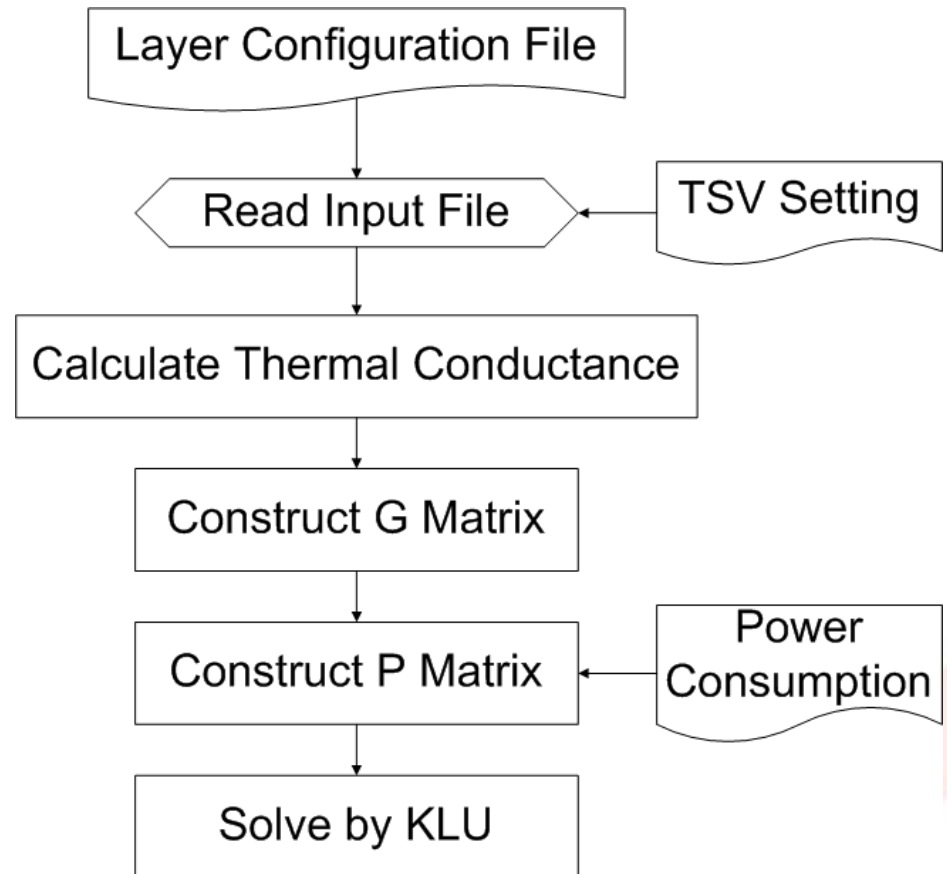
- **Sparse matrix equation is setup and solved by KLU [KLU]**

$$GT = P$$



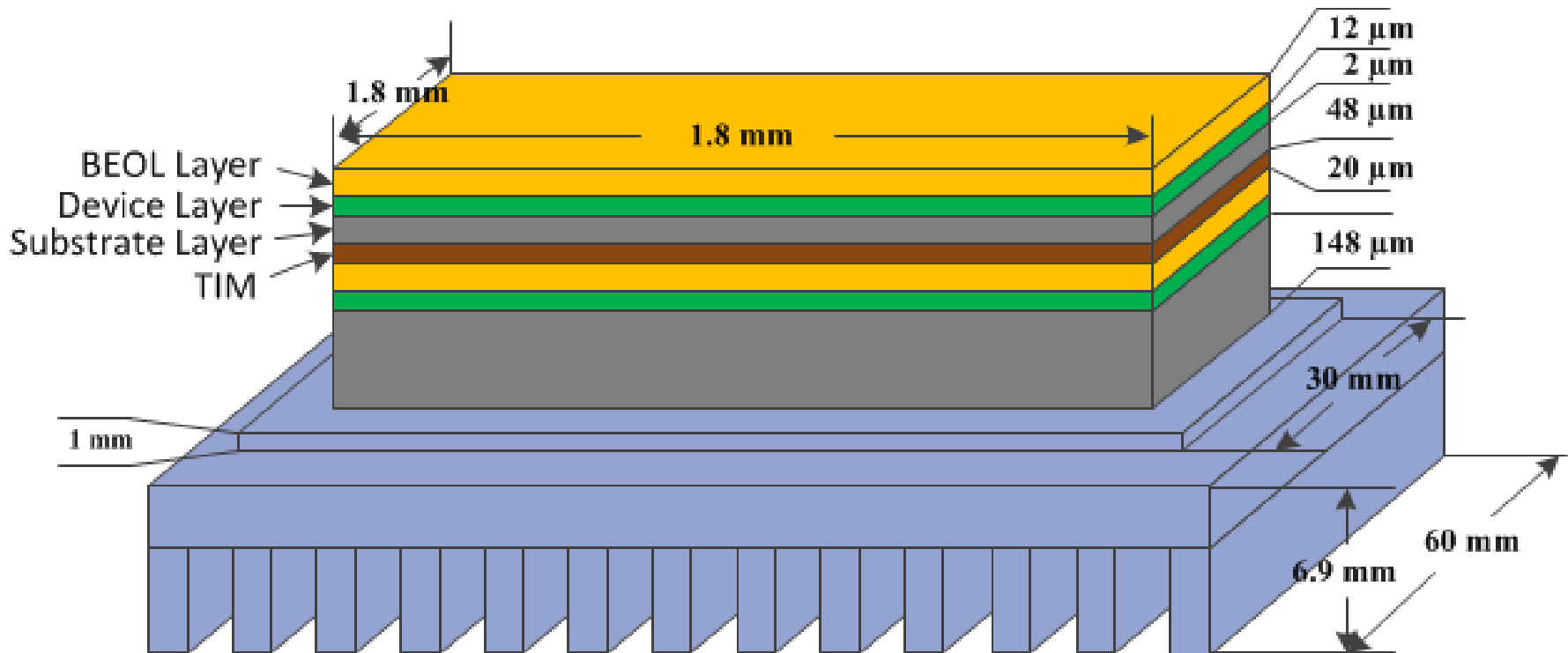
# 3D-ACME: Software Package

- **3D-ACME: 3D-IC thermal simulator with modeling of Anisotropic TSV Conductance and Microchannel Entrance effects**
  - Implemented in C
  - Released online at: <http://www.3dacme.allalla.com>



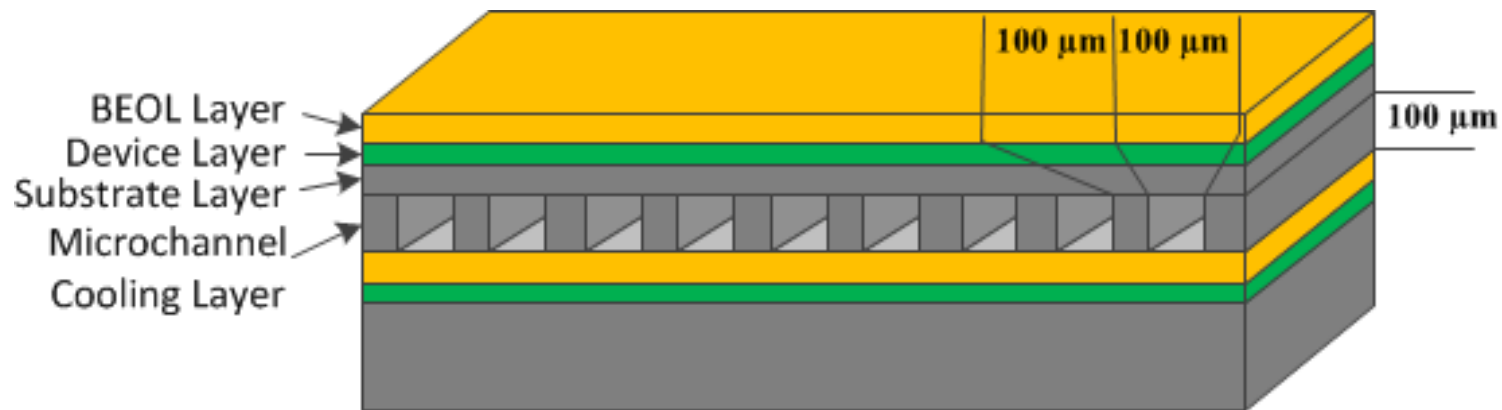
# Experiment Settings I

- Heatsink-cooled 2-layer 3D stack



# Experiment Settings II

- **Microfluidic-Cooled 2-layer 3D stack**



Default flow-rate	9 ml/min
Coolant type	Water

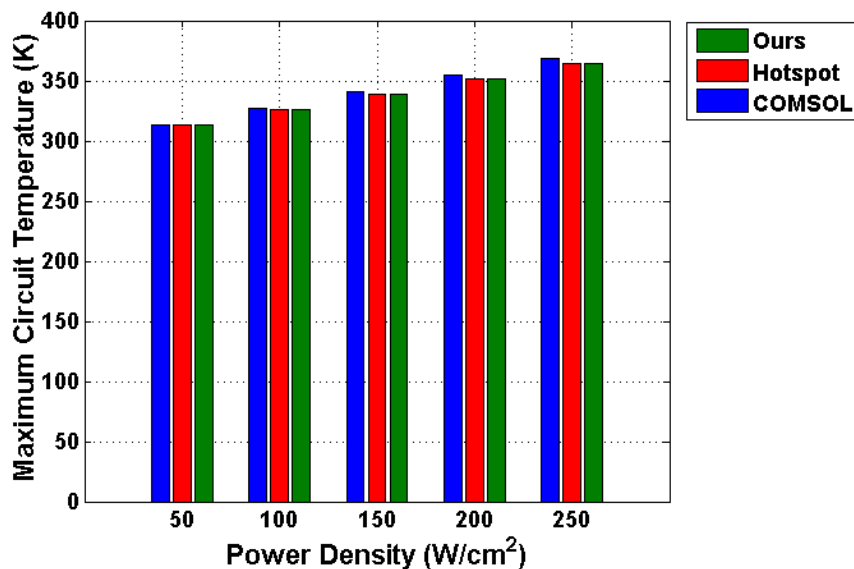
- **Power Setting:** uniform power density 50-250 W/cm<sup>2</sup>

# Accuracy Study: Heat-sink Cooling

## Comparison with COMSOL\* and Hotspot 5.0†

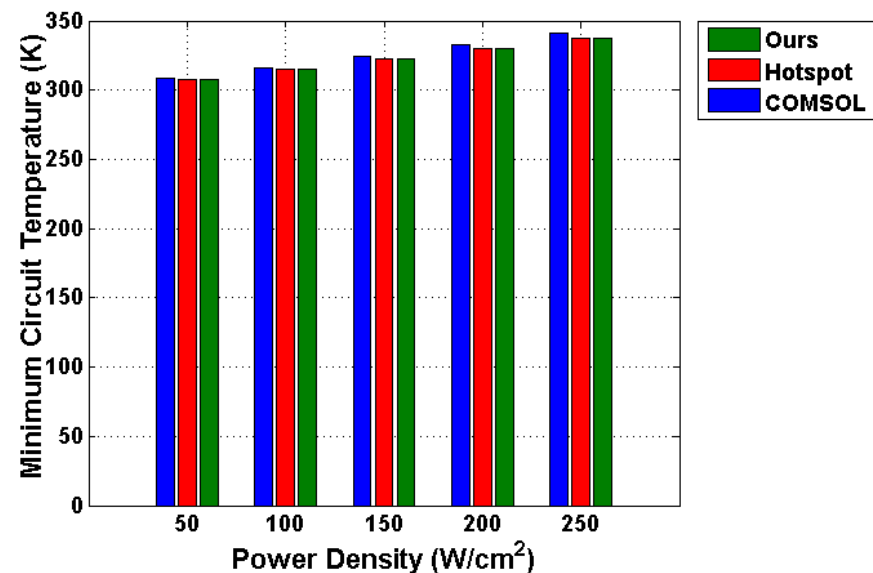
### Maximum Temperature

- Identical Result as Hotspot
- Less than 1.2% error against COMSOL



### Minimum Temperature

- Identical Result as Hotspot
- Error less than 1.1% against COMSOL



\* <http://www.comsol.com>

† <http://lava.cs.virginia.edu/HotSpot/>

# Runtime Study

## Comparison with COMSOL and Hotspot 5.0

- **Setup:** grid granularity is 16x16 with 2572 grid cells(16x16x10 sub-layers + 12 peripheral nodes of heat spreader and heat-sink)
- **Up to 21x speedup against COMSOL and Hotspot**
  - Hotspot depends on power levels with more iterations
  - Like COMSOL, runtime of our simulator only depends on problem size
  - Much faster than COMSOL due to less number of grid nodes converged in single-solving step

Simulator\ Power Density	50	100	150	200	250
COMSOL	42	42	42	42	42
Hotspot	0.763	1.019	1.187	1.31	1.41
Ours	0.068	0.068	0.059	0.061	0.066
Speedup	11x	15x	20x	21x	21x

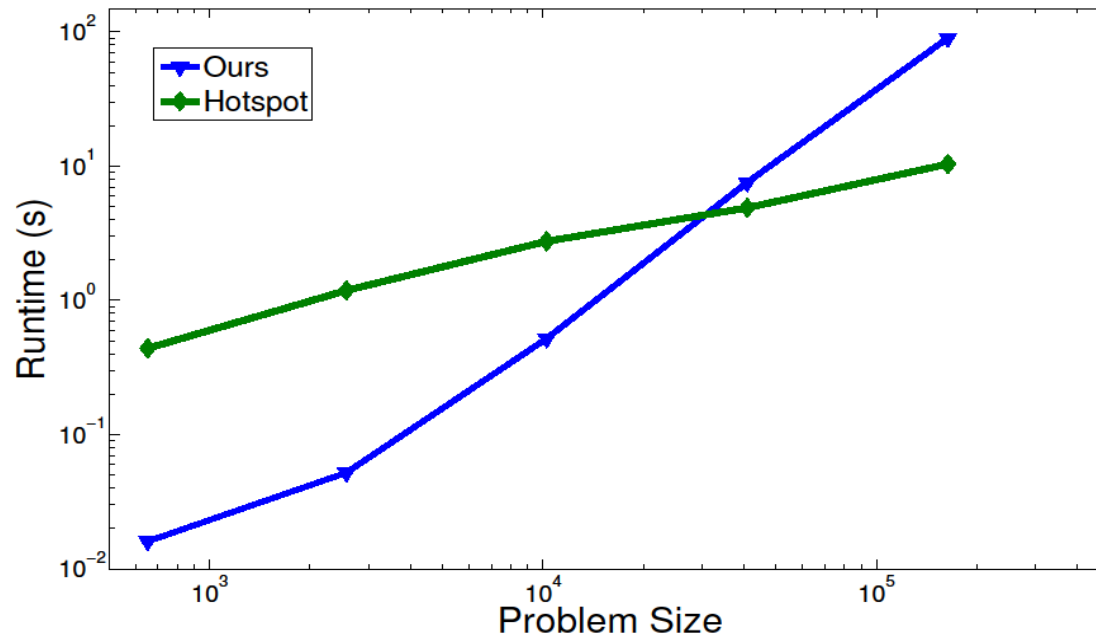
runtime in unit of *second*



# Scalability Study

## Comparison with Hotspot 5.0

- **Hotspot: Logarithmic Scaling**
  - Advantage for large size problem with grid granularity in the form of  $2^n \times 2^n$
- **Ours: Linear Scaling**
  - Advantage for small and medium size problem
  - No restriction on grid division, which is necessary for non-squared chip-modeling with microfluidic-cooling

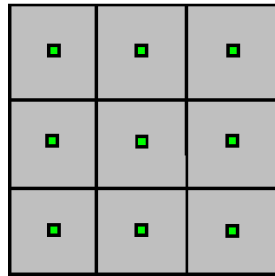


# Temperature Reduction by TSV Insertion

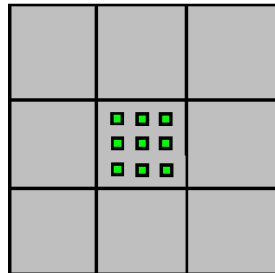
## Comparison with COMSOL

- Three patterns of TSV as test cases

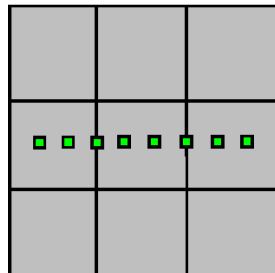
– Pattern A



– Pattern B



– Pattern C



- Compare reduction of maximum temperature due to TSV insertion

- Small deviation from COMSOL
- Acceptably accurate considering the 300K baseline temperature

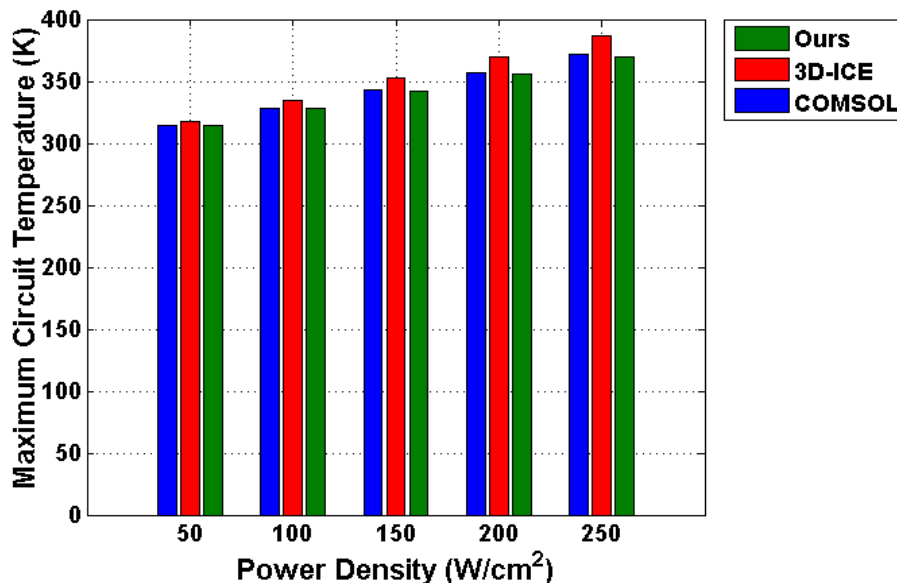
Pattern\PD		50	100	150	200	250
A	COMSOL	0.2	0.4	0.6	0.8	1
	Ours	0.31	0.63	0.94	1.26	1.57
	Error	0.11	0.23	0.34	0.46	0.57
B	COMSOL	0.14	0.29	0.44	0.59	0.73
	Ours	0.18	0.36	0.53	0.71	0.89
	Error	0.04	0.07	0.09	0.12	0.16
C	COMSOL	0.12	0.24	0.36	0.48	0.60
	Ours	0.16	0.31	0.47	0.63	0.78
	Error	0.04	0.07	0.11	0.15	0.18

# Accuracy Study: Microfluidic Cooling

## Comparison with COMSOL and 3D-ICE\*

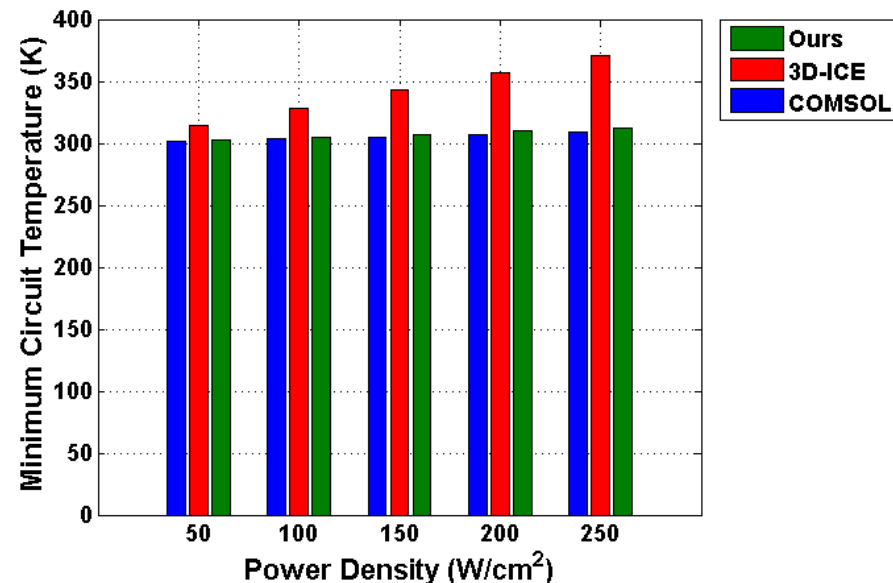
### Maximum Temperature

- More accurate than 3D-ICE
- Largest Error: Ours **0.5%** vs 3D-ICE **4.3%**



### Minimum Temperature

- Much more accurate than 3D-ICE
- Largest Error: Ours **1.1%** vs 3D-ICE **20.2%**

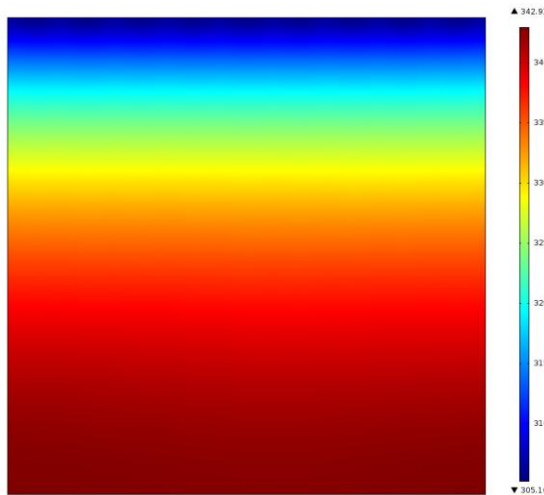


\* <http://esl.epfl.ch/3d-ice.html>

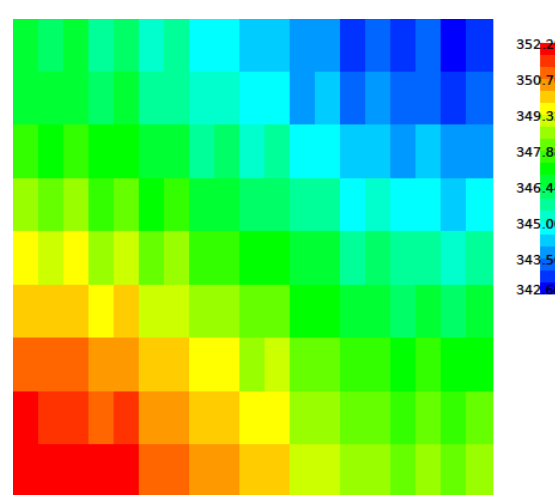
# Thermal Gradient Study

## Comparison with COMSOL and 3D-ICE

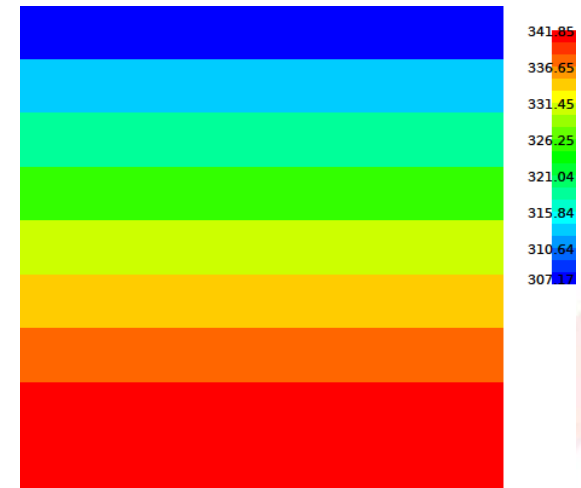
- **Correct thermal map is generated by our simulator 3D-ACME**
- **A slanted thermal distribution is generated by 3D-ICE with deviation from correct simulation**



COMSOL



3D-ICE



3D-ACME

# Conclusions

**3D-ACME:** <http://www.3dacme.allalla.com>

- **Compact 3D-IC thermal simulator considering both TSV anisotropic thermal effect and microchannel entrance effect**
- **Accurate estimation of steady state temperature for heat-sink and microfluidic-cooled 3D-IC**
  - Compared to Hotspot: similar accuracy, shorter runtime at moderate granularity, but with capability of TSV and microfluidic modeling.
  - Compared to 3D-ICE: much more accurate steady state simulation with capability of TSV anisotropic thermal modeling