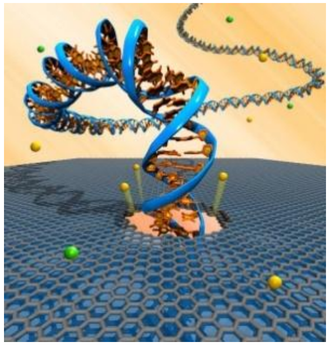
Thermal Simulator of 3D-IC with Modeling of Anisotropic TSV Conductance and Microchannel Entrance Effects

School of Electrical and Electronic Engineering,
Nanyang Technological University, Singapore

Hanhua Qian, Hao Liang, Chip-Hong Chang,
Wei Zhang and Hao Yu

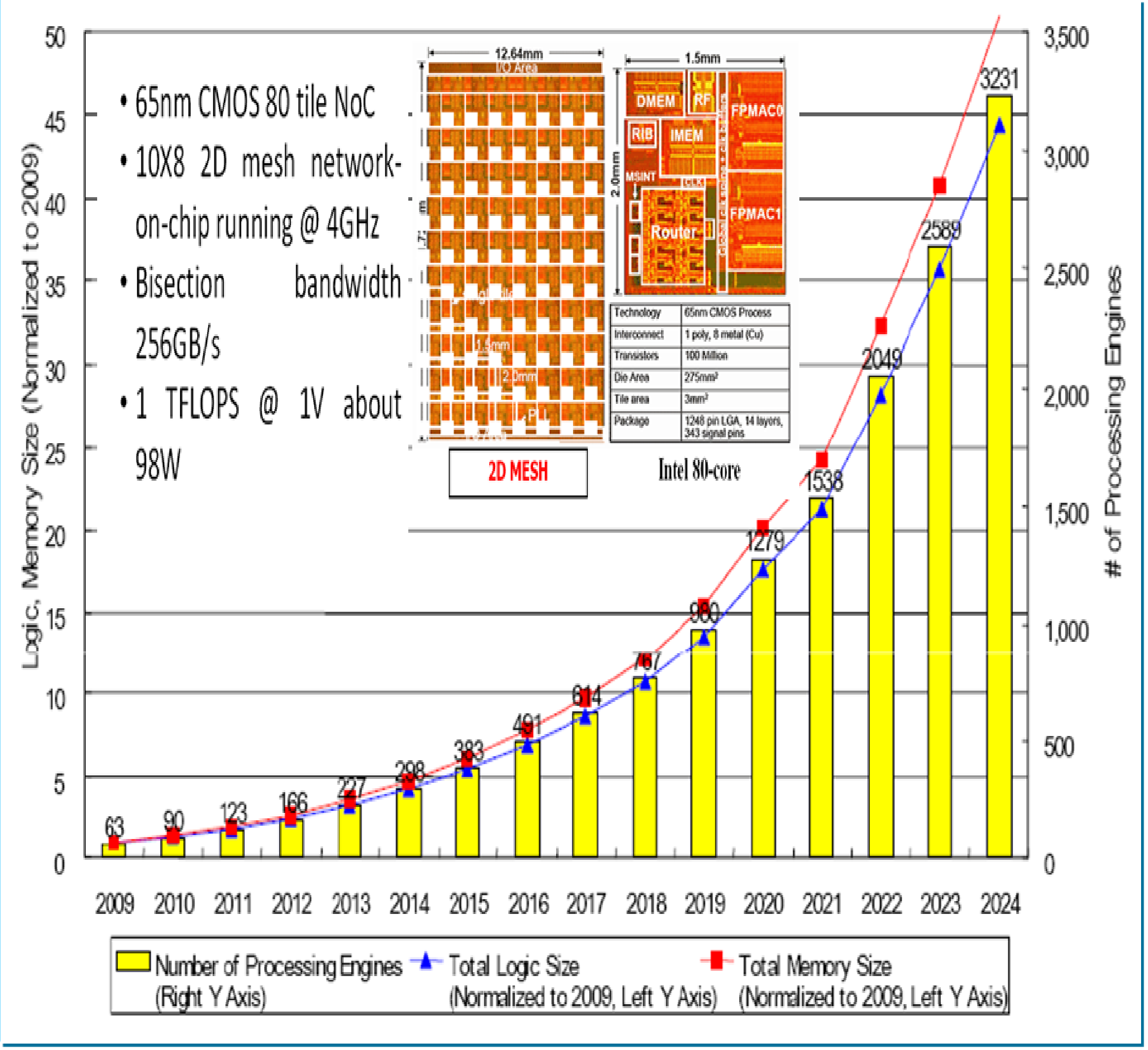
Big Data Era: from Teta (10^{15}) to Exa-scale (10^{18})

- **‘*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

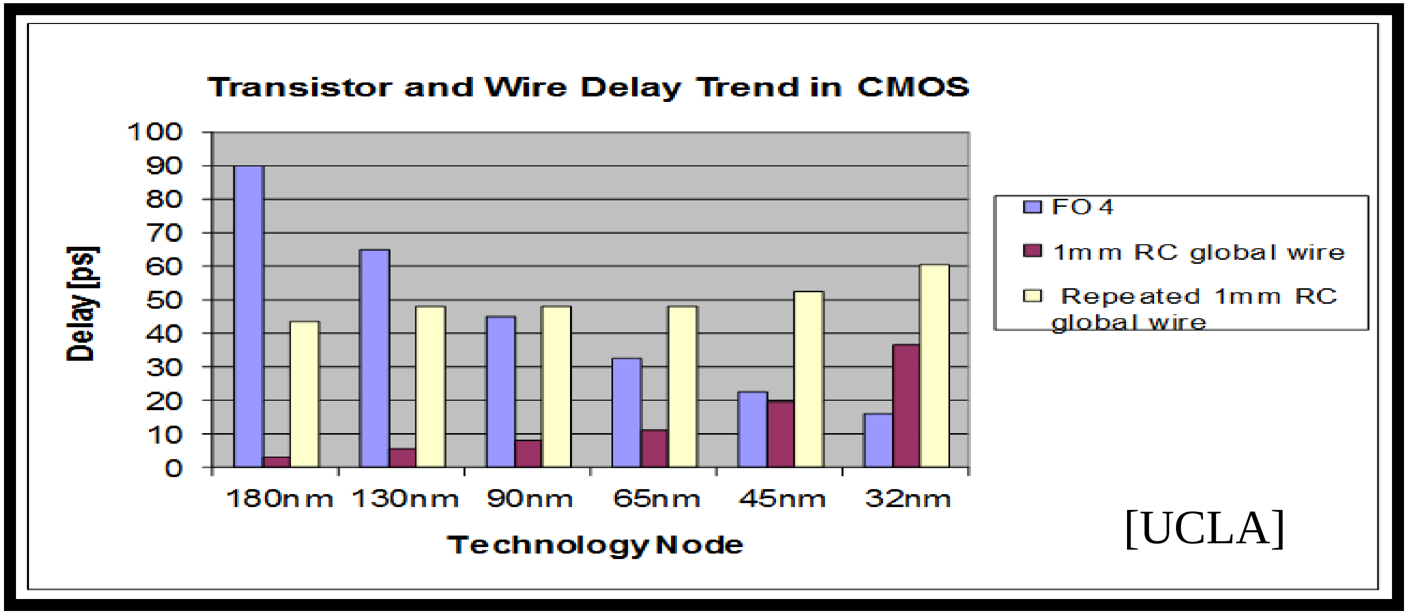


- 65nm CMOS 80 tile NoC
- 10X8 2D mesh network-on-chip running @ 4GHz
- Bisection bandwidth 256GB/s
- 1 TFLOPS @ 1V about 98W

Technology	65nm CMOS Process
Interconnect	1 poly, 8 metal (Cu)
Transistors	100 Million
Die Area	275mm²
Tile area	3mm²
Package	1248 pin LGA, 14 layers, 343 signal pins

- 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

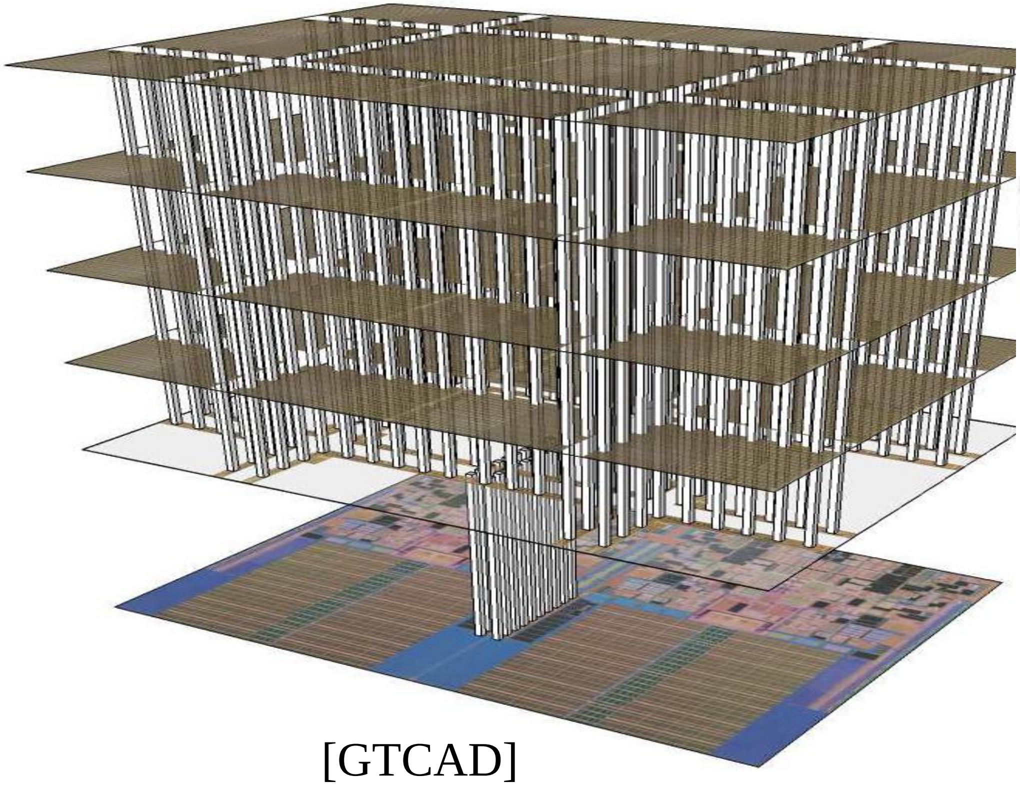
2D Interconnect Scaling Slow-down



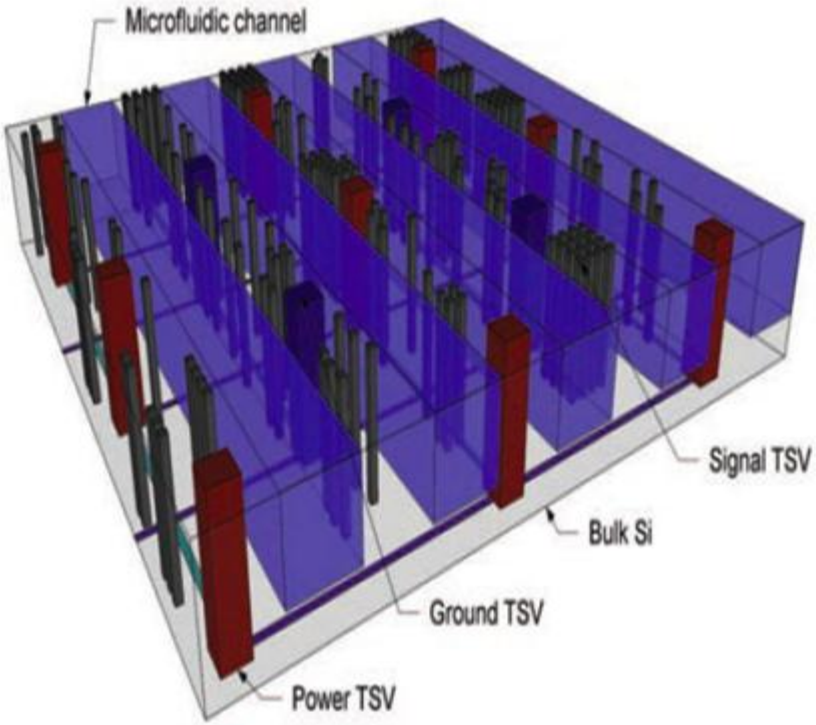
[UCLA]

- **Wire (L) latency not scaling down**
  - Voltage signal charging/discharging of cap: RC-limited (~L^2) and reduced with repeater (~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?



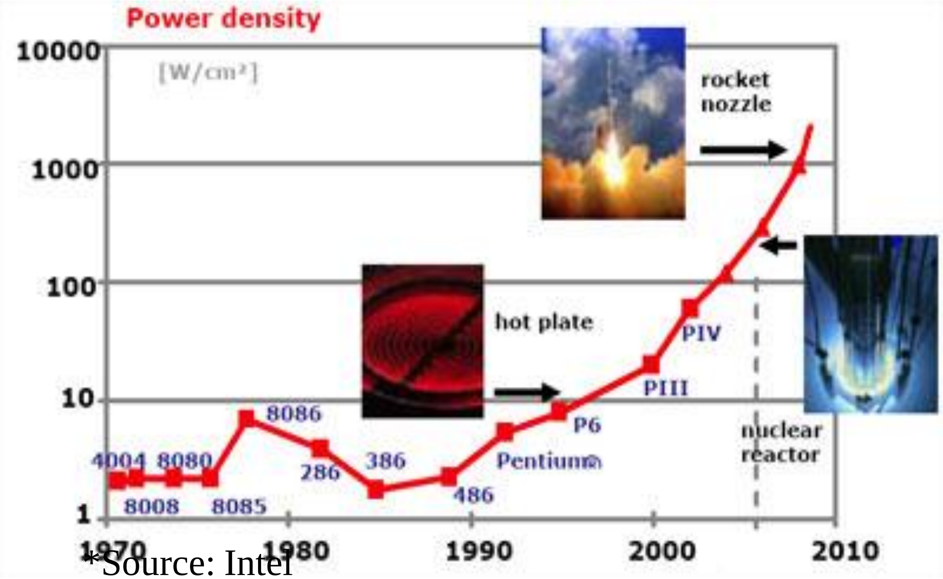
[GTCAD]



- **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**



*Source: Intel

- **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

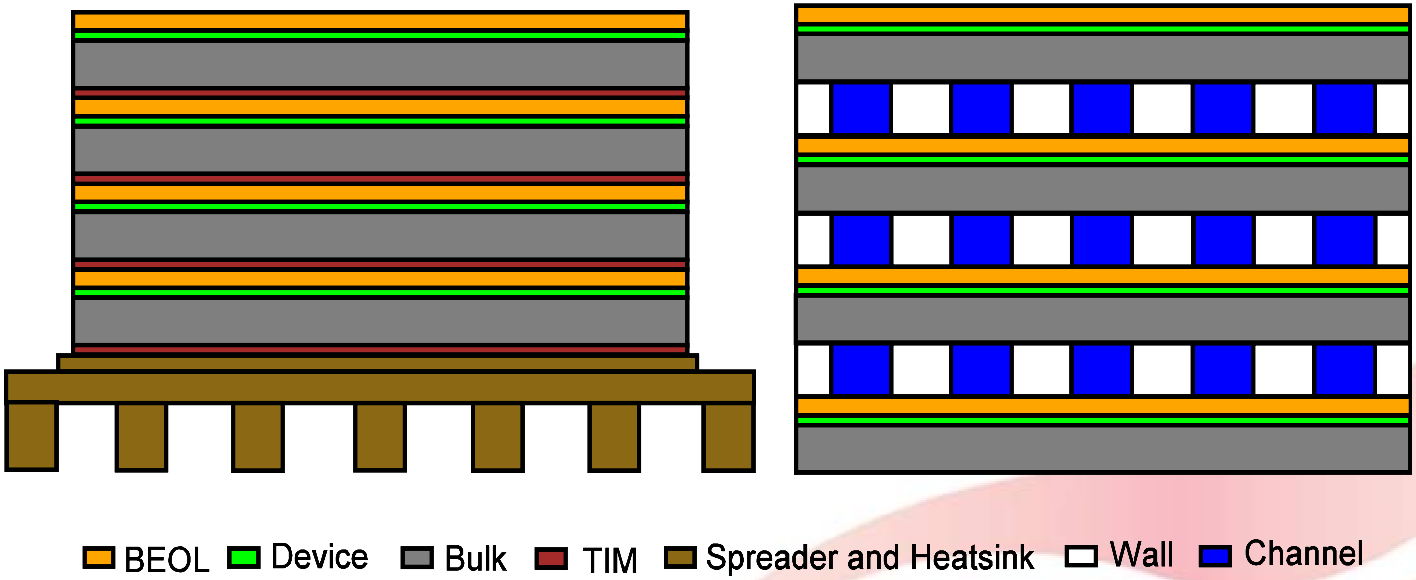
- **A fast and accurate thermal simulator is needed for 3D thermal management**
- **Available Options:**

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

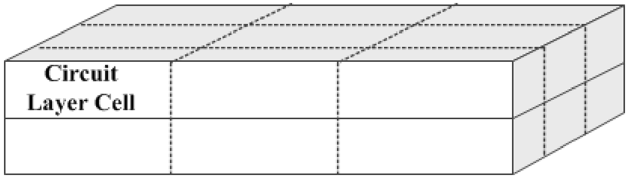
  - Hotspot [Huang04]: lack of microfluidic cooling model.
  - 3D-ICE [Sridhar10]: Ignorance of microchannel entrance effects
  - Both Hotspot and 3D-ICE have not considered model specifically TSV anisotropic thermal effect

Targeted Problem

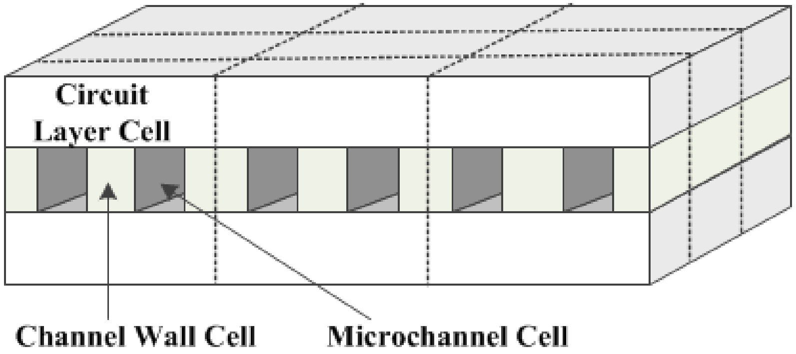
- **Model both heat-sink-based air-cooling and microfluidic cooling**
- **Layer composition:**
  - Back End of Lines (BEOL), Devices, and Bulk Sub-layers
- **TSV anisotropic effect and microchannel entrance effect**



Modeling Methodology



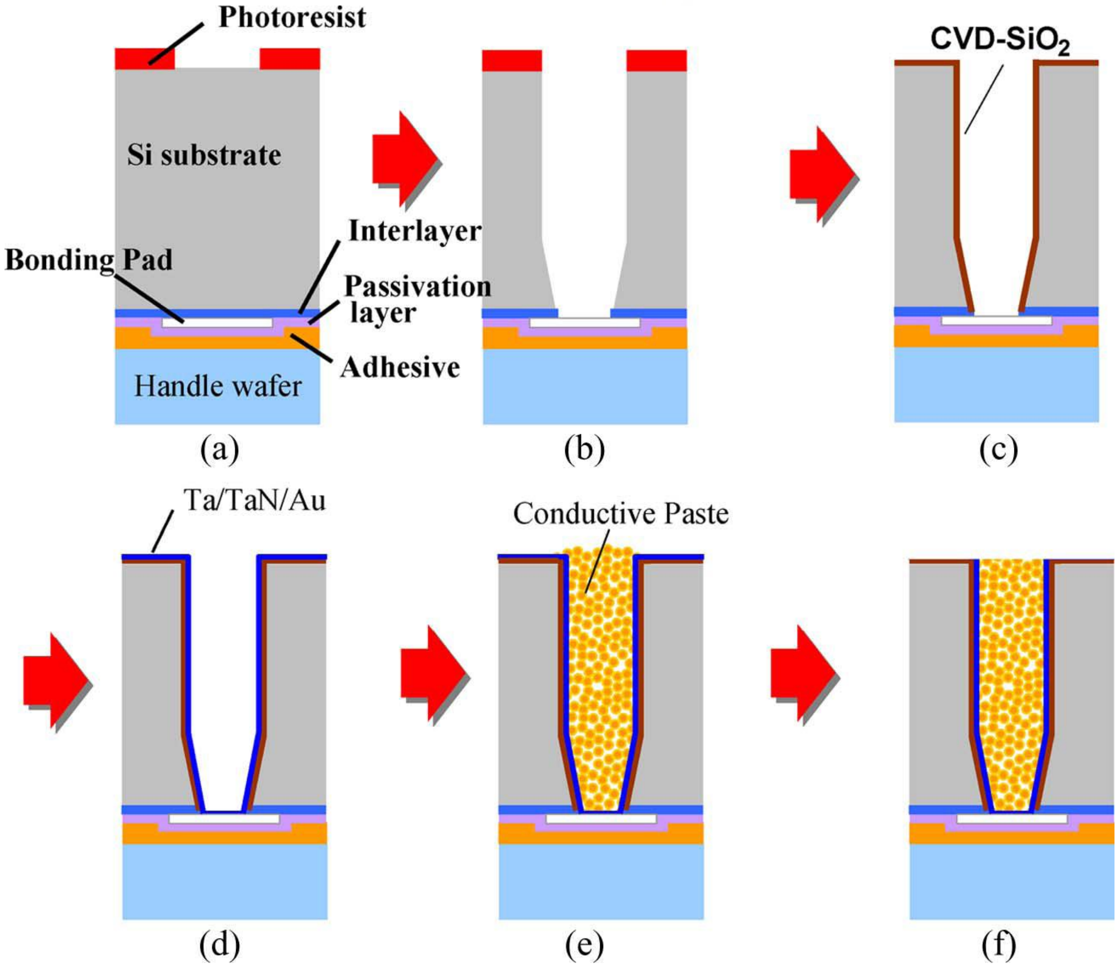
Heatsink-Cooled (Circuit Part Only)



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



Source: [Motoyoshi09]

- **Back side lithography;**
- **Deep Si-etch and SiO2 RIE;**
- **SiO2 deposition and RIE;**
- **Contact metal/barrier metal deposition;**
- **Paste printing;**
- **Contact and barrier metal removal.**

- **Typical Dimension**: d_m: 5-20 μm; d_l: ~0.25 μm

- **Typical Thermal**: k_{liner}= 30 W/(mK); k_{metal} = 400 W/(mK) for Si_3N_4 liner and Copper fill

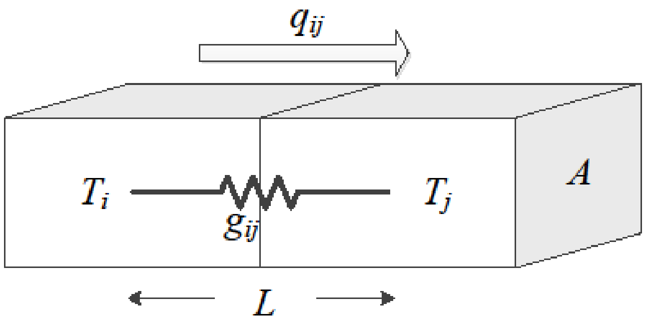
Significance of TSV Anisotropic Effect

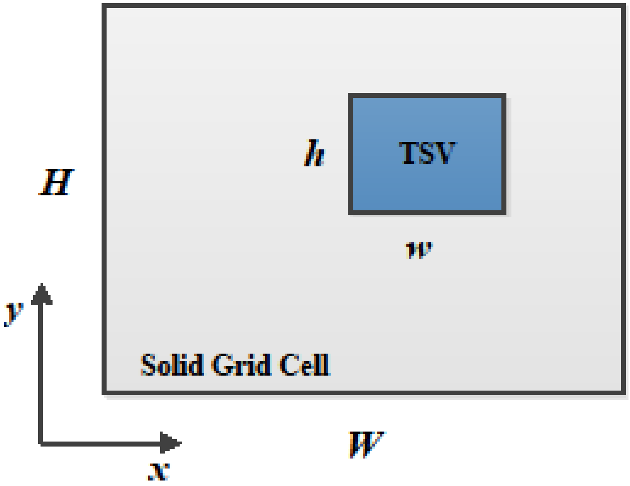
- **Metal TSV as filling material**
  - Good heat conductivity
- **Silicon oxide as liner**
  - Thermal insulator with poor heat conductivity
- **TSV Anisotropic Effect: different heat conduction properties along different direction**
  - Heat conductivity in 3D-IC depends on size and location
  - Simple 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**

$$g_{ij} = kA/L$$





- **With TSV inserted**

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

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

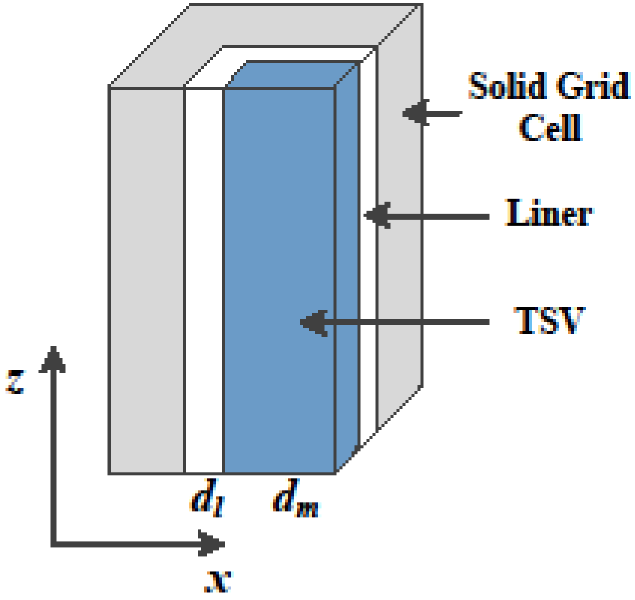
$$g_z = (1 + \frac{wh(\beta - 1)}{WH})g_{z0}$$

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

β: 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



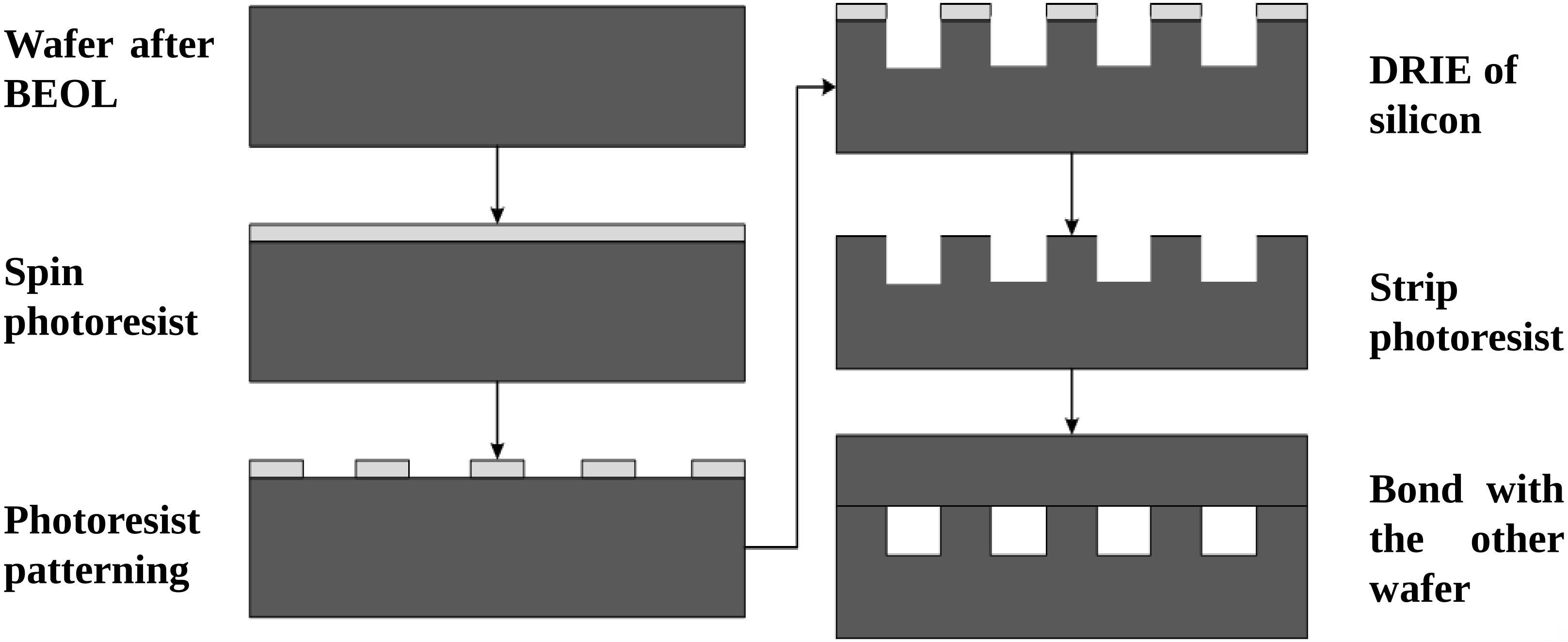
$$k_{TSV,xy} = (1 + \frac{d_m^2(\gamma - 1)}{(d_m + 2d_l)(d_m + 2d_l\gamma)})k_{liner}$$

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

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

Microchannel Device Fabrication

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



Wafer after BEOL

Spin photoresist

Photoresist patterning

DRIE of silicon

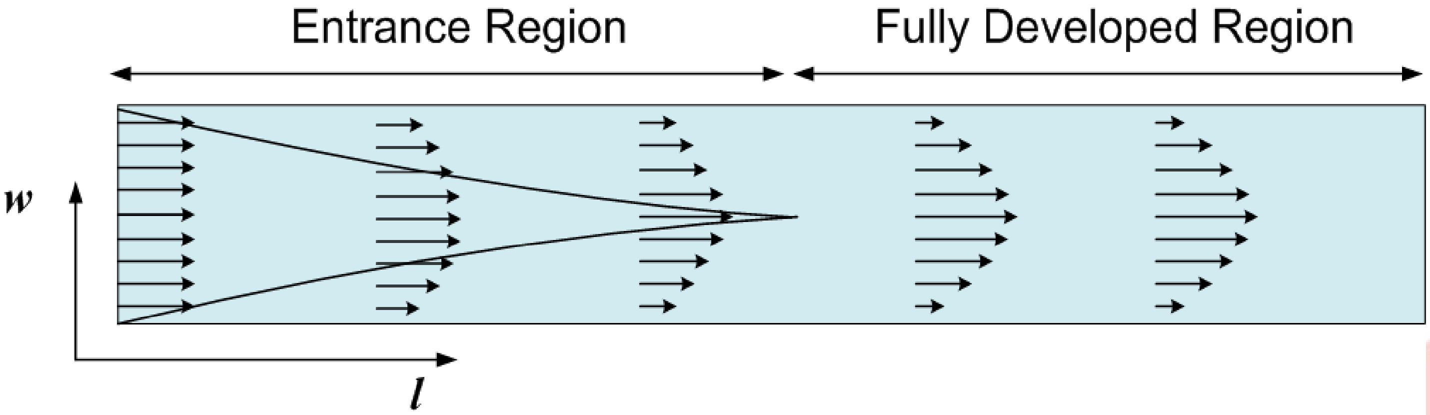
Strip photoresist

Bond with the other wafer

Typical Microchannel Width: 50-200 μm;
Typical Microchannel Height: 50-200 μm;
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

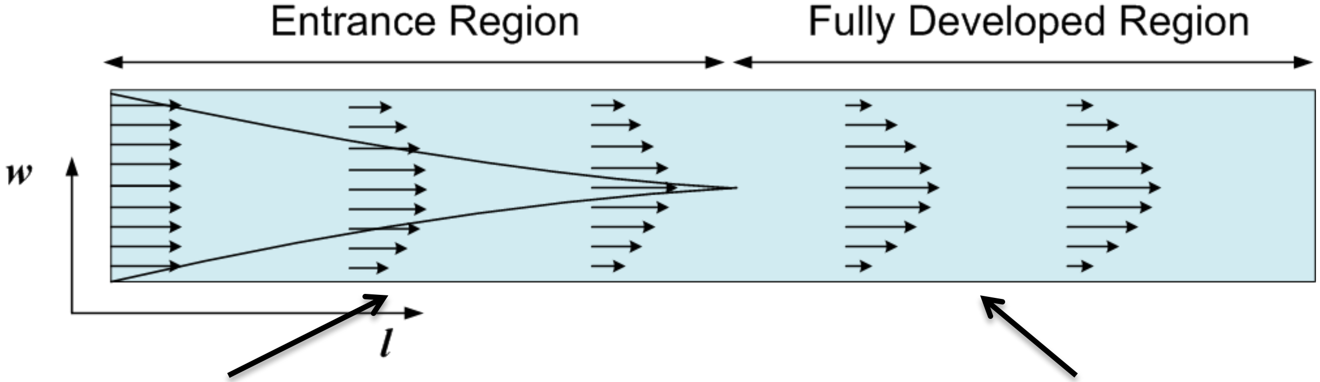


Model of Microfluidic Entrance Effect I

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

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

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

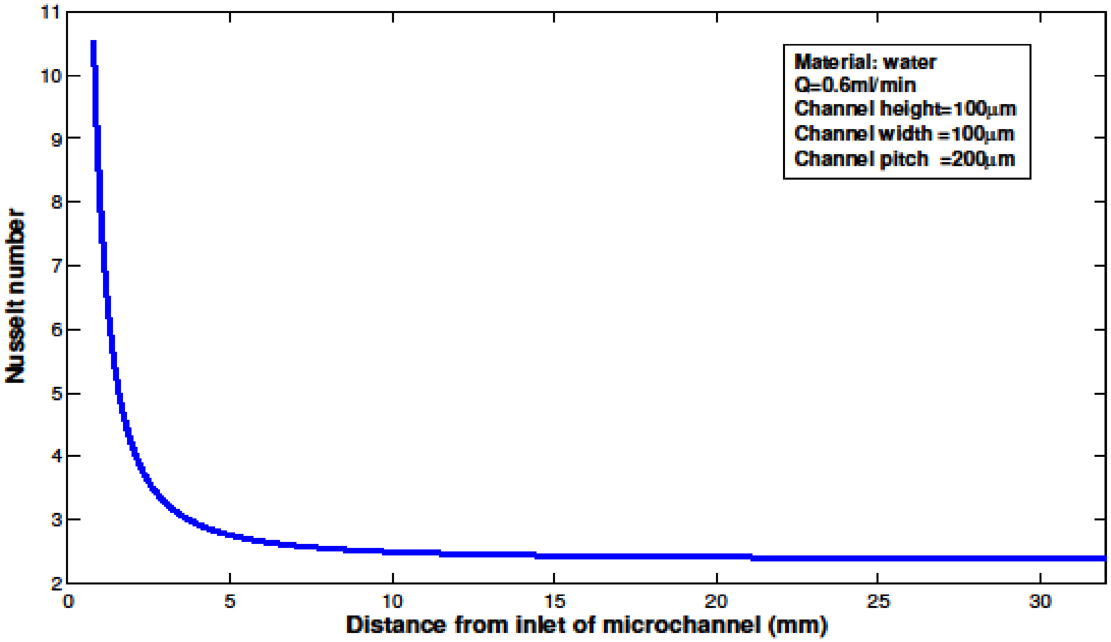


$$Nu_{st} = Nu_0 (\mathrm{Re} \cdot \mathrm{Pr})^{1/3} (\frac{D_H}{l})^{\eta} \qquad Nu_{pp} = 0.1165 (\frac{D_H}{Pitch})^{0.81} (\frac{H_{ch}}{W_{ch}})^{-0.79} \mathrm{Re}^{0.62} \mathrm{Pr}^{1/3}$$

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

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 severes under-estimation of spatial thermal gradient



Steady State Simulation under Thermal Balance

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

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

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

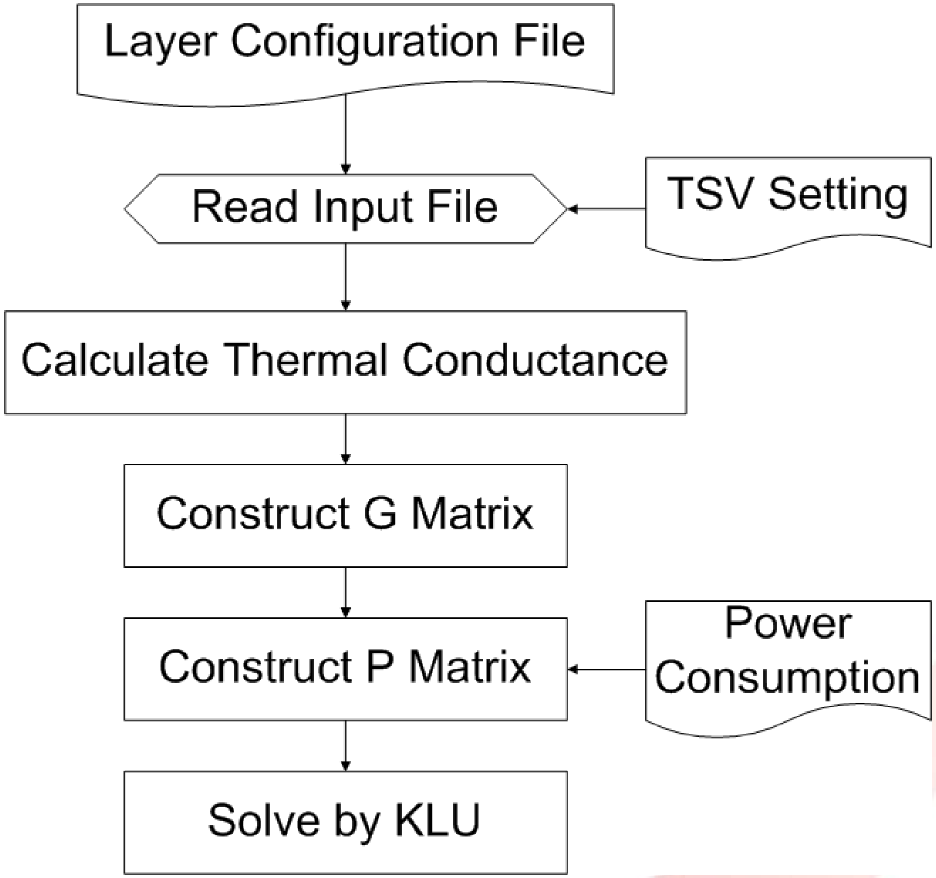
$$\sum_{j \in \{walls\}} g_{ch,i,j} (T_{ch,i} - T_j) = (T_{ch,i} - T_{ch,i-1}) Q C_V$$

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

$$GT = P$$

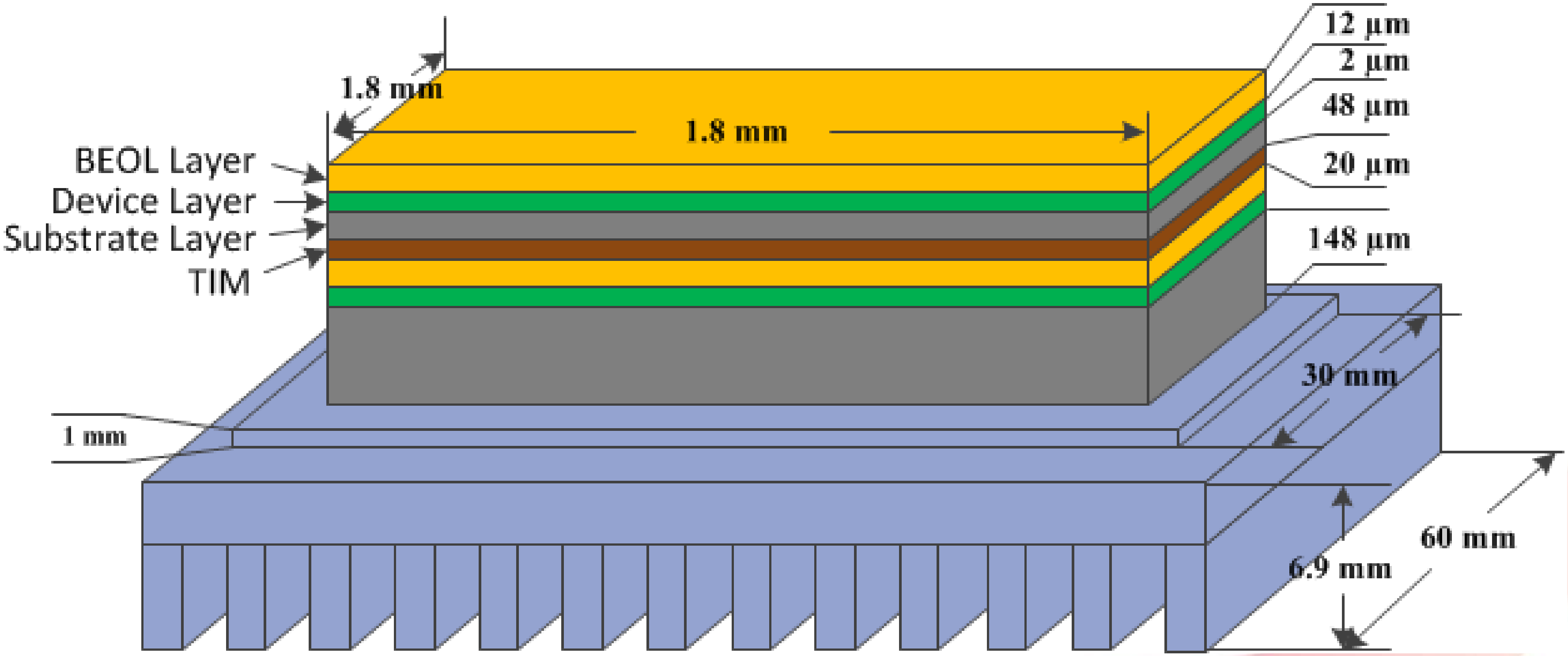
3D-ACME: Software Package

- **3D-ACME: 3D**-IC thermal simulator with modeling of **A**nisotropic TSV **C**onductance and **M**icrochannel **E**ntrance effects
  - Implemented in C
  - Released online at: http://www.3dacme.allalla.com



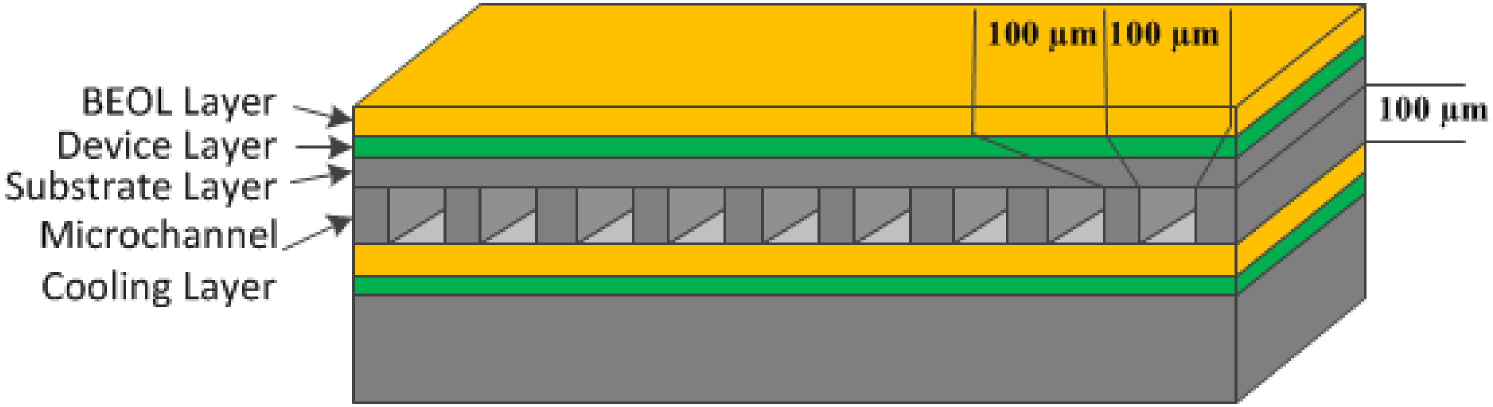
Experiment Settings I

- **Heatsink-cooled 2-layer 3D stack**



Experiment Settings II

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



Default flow-rate	9 ml/min
Coolant type	Water

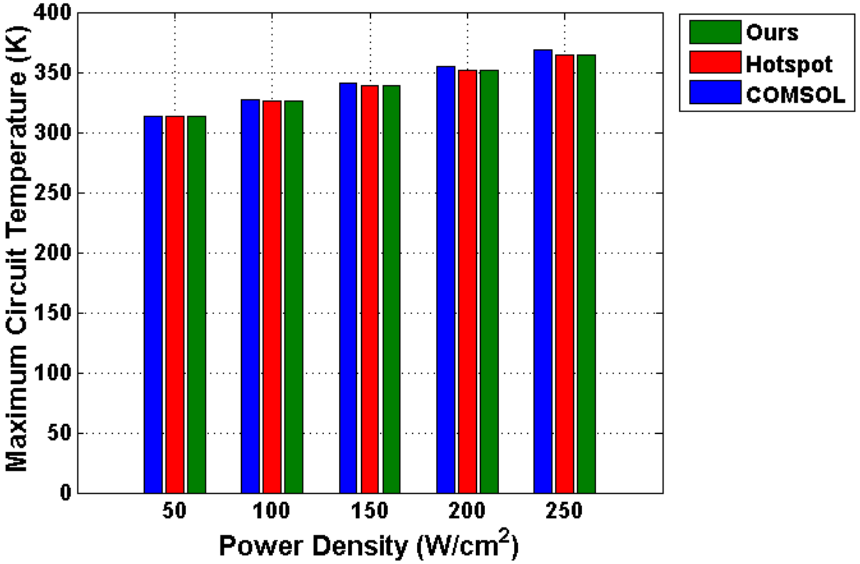
- **Power Setting:** uniform power density 50-250 W/cm^2

Accuracy Study: Heat-sink Cooling

Comparison with COMSOL* and Hotspot 5.0†

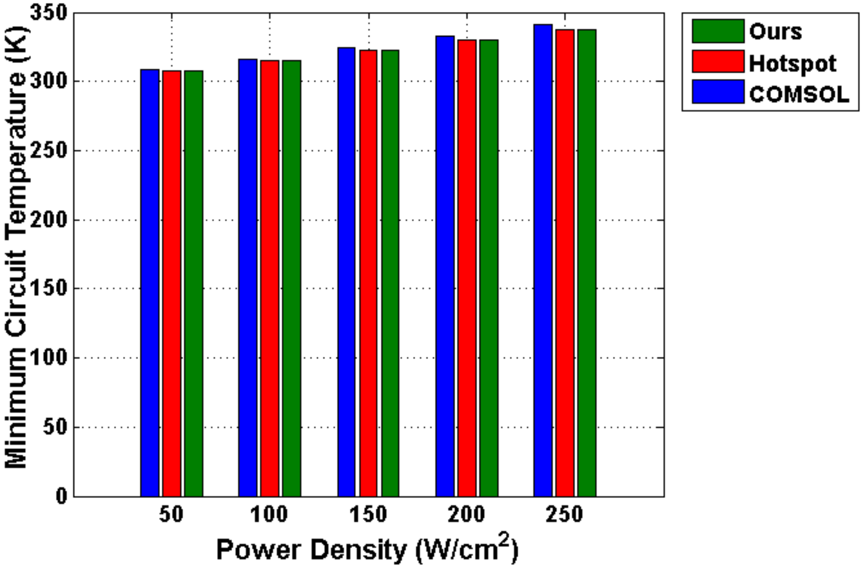
Maximum Temperature

- 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

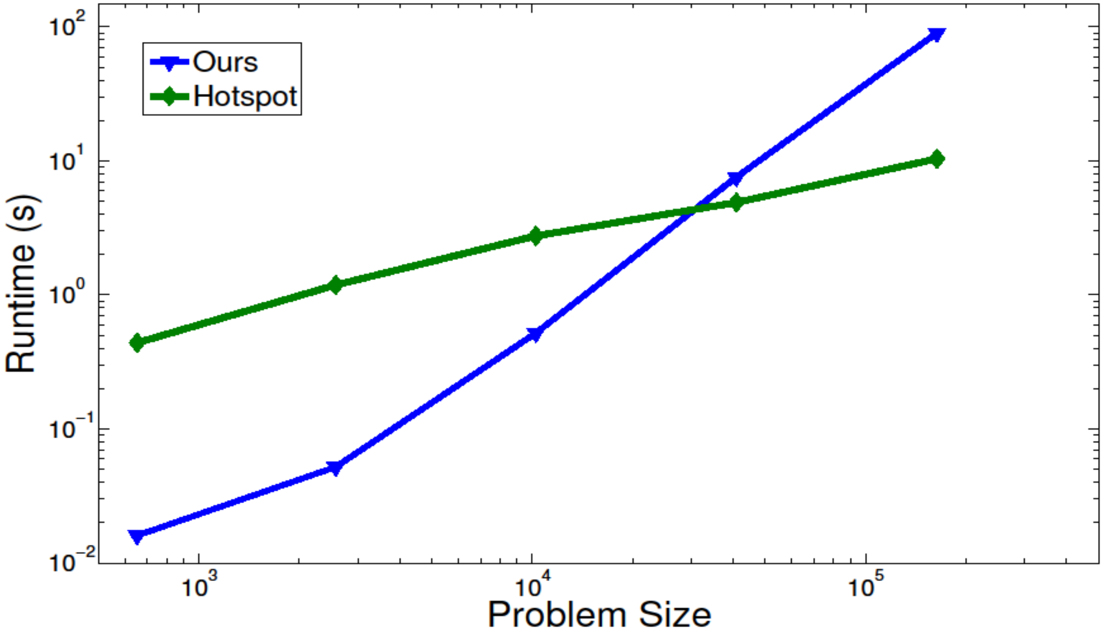
Simulator\ Power Density	**50**	**100**	**150**	**200**	**250**
COMSOL	42	42	42	42	42
Hotspot	0.763	1.019	1.187	1.31	1.41
Ours	0.068	0.068	0.059	0.061	0.066
Speedup	11x	15x	20x	21x	21x

runtime in unit of *second*

Scalability Study

Comparison with Hotspot 5.0

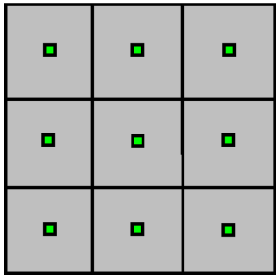
- **Hotspot: Logarithmic Scaling**
  - Advantage for large size problem with grid granularity in the form of $2^n x 2^n$
- **Ours: Linear Scaling**
  - Advantage for small and medium size problem
  - No restriction on grid division, which is necessary for non-squared chip-modeling with microfluid-cooling



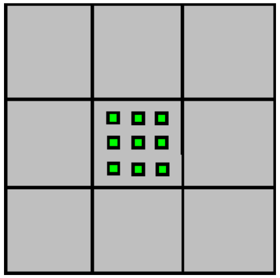
Temperature Reduction by TSV Insertion

Comparison with COMSOL

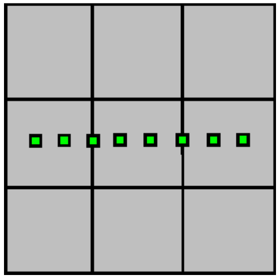
- **Three patterns of TSV as test cases**
  - Pattern A



  - Pattern B



  - Pattern C



- **Compare reduction of maximum temperature due to TSV insertion**
  - Small deviation from COMSOL
  - Acceptably accurate considering the 300K baseline temperature

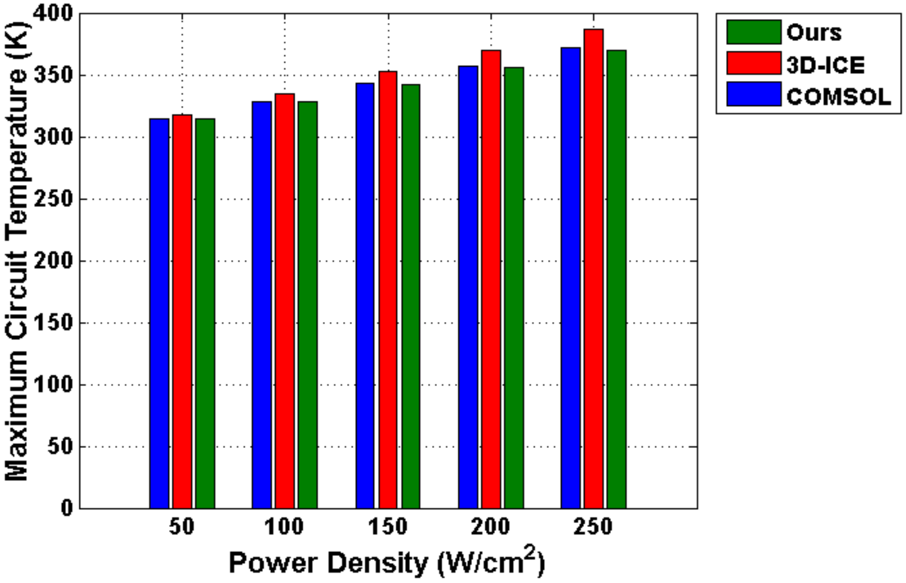
Pattern\PD		**50**	**100**	**150**	**200**	**250**
A	COMSOL	0.2	0.4	0.6	0.8	1
	Ours	0.31	0.63	0.94	1.26	1.57
	Error	0.11	0.23	0.34	0.46	0.57
B	COMSOL	0.14	0.29	0.44	0.59	0.73
	Ours	0.18	0.36	0.53	0.71	0.89
	Error	0.04	0.07	0.09	0.12	0.16
C	COMSOL	0.12	0.24	0.36	0.48	0.60
	Ours	0.16	0.31	0.47	0.63	0.78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

Accuracy Study: Microfluidic Cooling

Comparison with COMSOL and 3D-ICE*

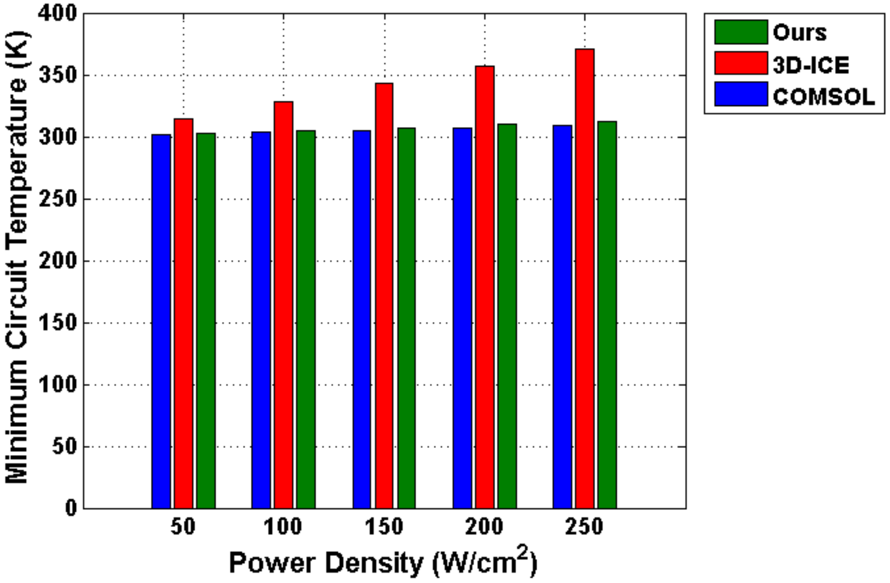
Maximum Temperature

- 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%**

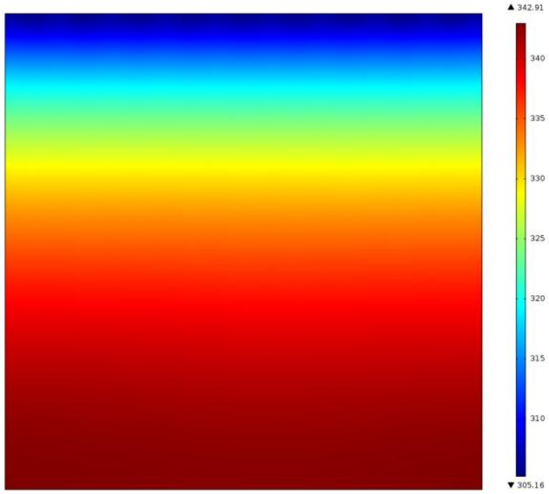


* http://esl.epfl.ch/3d-ice.html

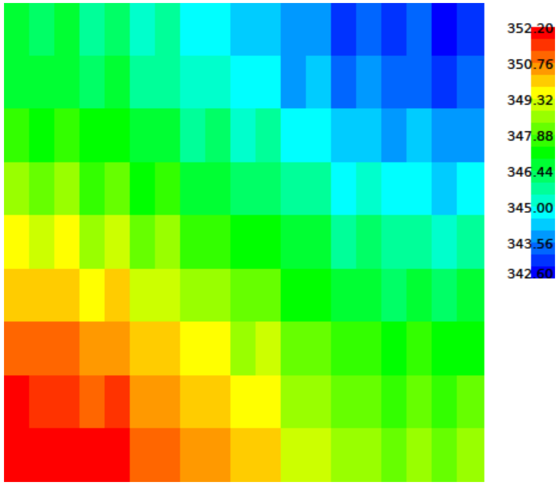
Thermal Gradient Study

Comparison with COMSOL and 3D-ICE

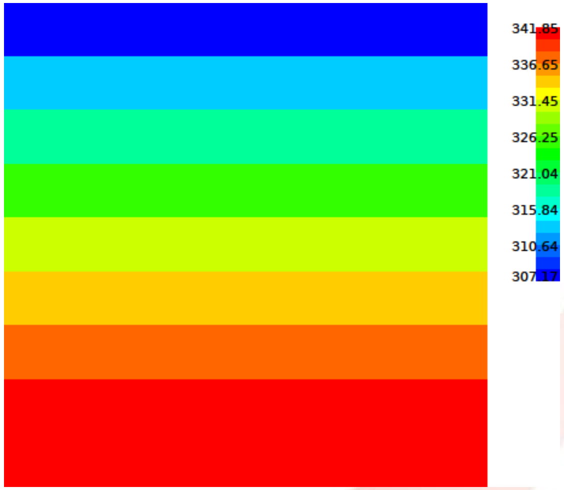
- **Correct thermal map is generated by our simulator 3D-ACME**
- **A slanted thermal distribution is generated by 3D-ICE with deviation from correct simulation**



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