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

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

- **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?

- 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

[GT CAD]
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]

*Source: Intel*
Need of 3D Thermal Simulator

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

<table>
<thead>
<tr>
<th>Commercial Numerical Simulator</th>
<th>Available Open Source Simulator</th>
</tr>
</thead>
<tbody>
<tr>
<td>General and accurate</td>
<td>Specific, moderately accurate</td>
</tr>
<tr>
<td>Long simulation time</td>
<td>Significant speedup</td>
</tr>
<tr>
<td>Subject to charges</td>
<td>Open source available</td>
</tr>
<tr>
<td>ANSYS, COMSOL</td>
<td>Hotspot, 3D-ICE</td>
</tr>
</tbody>
</table>

– 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

- **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

Heatsink-Cooled (Circuit Part Only)  Microfluidic-Cooled
TSV Device Fabrication

• 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 \( \mu \)m; \( d_i \): \sim 0.25 \( \mu \)m
- Typical Thermal: \( k_{\text{liner}} = 30 \) W/(mK); \( k_{\text{metal}} = 400 \) W/(mK) for Si\(_3\)N\(_4\) 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**
  \[ g_{ij} = kA / L \]

- **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

\( \beta \): 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

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

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

\[
\gamma = \frac{k_{metal}}{k_{liner}}
\]
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 $h$

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

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

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

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

![Graph showing Nusselt number vs. distance from inlet of microchannel](image-url)
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

\[ \sum_{j \in \{walls\}} g_{ch,i,j} (T_{ch,i} - T_j) = (T_{ch,i} - T_{ch,i-1}) QC_V \]

• 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](http://www.3dacme.allalla.com)
Experiment Settings I

- Heatsink-cooled 2-layer 3D stack
Experiment Settings II

• Microfluidic-Cooled 2-layer 3D stack

<table>
<thead>
<tr>
<th>Default flow-rate</th>
<th>9 ml/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coolant type</td>
<td>Water</td>
</tr>
</tbody>
</table>

• **Power Setting:** uniform power density 50-250 W/cm²
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

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

<table>
<thead>
<tr>
<th>Simulator\Power Density</th>
<th>50</th>
<th>100</th>
<th>150</th>
<th>200</th>
<th>250</th>
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<tbody>
<tr>
<td>COMSOL</td>
<td>42</td>
<td>42</td>
<td>42</td>
<td>42</td>
<td>42</td>
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<tr>
<td>Hotspot</td>
<td>0.763</td>
<td>1.019</td>
<td>1.187</td>
<td>1.31</td>
<td>1.41</td>
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<tr>
<td>Ours</td>
<td>0.068</td>
<td>0.068</td>
<td>0.059</td>
<td>0.061</td>
<td>0.066</td>
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<tr>
<td>Speedup</td>
<td>11x</td>
<td>15x</td>
<td>20x</td>
<td>21x</td>
<td>21x</td>
</tr>
</tbody>
</table>

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 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

<table>
<thead>
<tr>
<th>Pattern\PD</th>
<th>50</th>
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<th>150</th>
<th>200</th>
<th>250</th>
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<tbody>
<tr>
<td>A</td>
<td>COMSOL 0.2</td>
<td>0.4</td>
<td>0.6</td>
<td>0.8</td>
<td>1</td>
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<tr>
<td></td>
<td>Ours 0.31</td>
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<td>0.34</td>
<td>0.46</td>
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<tr>
<td>B</td>
<td>COMSOL 0.14</td>
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<td>0.44</td>
<td>0.59</td>
<td>0.73</td>
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<tr>
<td></td>
<td>Ours 0.18</td>
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<td>0.71</td>
<td>0.89</td>
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<td>0.07</td>
<td>0.09</td>
<td>0.12</td>
<td>0.16</td>
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<tr>
<td>C</td>
<td>COMSOL 0.12</td>
<td>0.24</td>
<td>0.36</td>
<td>0.48</td>
<td>0.60</td>
</tr>
<tr>
<td></td>
<td>Ours 0.16</td>
<td>0.31</td>
<td>0.47</td>
<td>0.63</td>
<td>0.78</td>
</tr>
<tr>
<td></td>
<td>Error 0.04</td>
<td>0.07</td>
<td>0.11</td>
<td>0.15</td>
<td>0.18</td>
</tr>
</tbody>
</table>
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
Conclusions

**3D-ACME:**  [http://www.3dacme.allalla.com](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