Leakage Power Characterization and Minimization in 3D Stacked Multi-core Chips with Microfluidic Cooling

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Objective

- To characterize leakage power in 3D multi-core architecture as a function of the cooling design
  
  ✓ Evaluate the leakage reduction for the optimized pin fin

- To study the impact of frequency scaling in a 3D multi-core architecture with microfluidic pin fin cooling on performance speedup, power consumption and energy efficiency

Infograph: Pascal Coderay, pascal@salut.ch
Background

3D Stacked ICs:
IC tiers are vertically integrated in a compact package.
- Length of global wires reduced by 50%\textsuperscript{[1]}
- Wire-limited frequency increased by 3.9X\textsuperscript{[1]}
- Wire-limited area and power reduced by 84% and 51%\textsuperscript{[1]}
- High communication bandwidth between tiers
- Heterogeneous tiers with multi-functionality

The Challenges:
The thermal issues become pronounced, ultimately downgrading system performance.
- Highly increased heat dissipation and power density
- Non-uniformity heat flux leads to hotspot
- Strong thermal coupling between tiers

Why Microfluidic Cooling?

Liquid cooling with surface enhancement such as pin fin is a viable solution to reduce the thermal stress in 3D stacked structures.

Back Side Air Cooling  
Cu heat spreader  
Tier 4  
Tier 3  
Tier 2  
Tier 1  
BT substrate  
PCB  

HTC: 25-250 W/m²-K[^2]

Pin Fin Enhanced Cooling  
Fluid  
Tier 4  
Tier 3  
Tier 2  
Tier 1  
BT substrate  
PCB  

HTC: 100-20000 W/m²-K[^2]

HTC is short for Heat Transfer Coefficient

System Architecture

Nehalem-like, Out-of-Order cores;
3GHz, 1.0V, max temp 373K
Issue width 4, ROB size 128
DL1: 128KB, 4096 sets, 64B
IL1: 32KB, 256 sets, 32B

Floor plan is built upon 16nm technology

Convection air cooling:
Temperature: 300K

L2 (per core): 2MB, 4096 sets, 128B, 35 cycles

L2 is shared among cores

16 symmetric cores

Linux OS
Parsec
SPEC
Splash-2
Compact Thermal Model (CTM)

Control volume around one pin

Energy balance for Solid:

\[ \dot{q}_{\text{gen}} + \dot{q}_{\text{cond}} + \dot{q}_{\text{conv}} = 0 \]

Energy balance for Fluid:

\[ \dot{m}C_p(T_{f,\text{in}} - T_{f,\text{out}}) + \dot{q}_{\text{conv}} = 0 \]

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness</th>
<th>Thermal Cond.</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO2&amp;Metal</td>
<td>10 ( \mu )m</td>
<td>1.4 W/m-K</td>
</tr>
<tr>
<td>Silicon</td>
<td>100 ( \mu )m</td>
<td>149 W/m-K</td>
</tr>
</tbody>
</table>
Pin Fin Optimization Process

Constraints
- pump power

Objectives
- Minimize the junction temperature and thermal resistance

Determine pin fin geometries, flow rate, etc.

Workload driven

Optimization Algorithm:
Genetic algorithm is used to do the optimization. The compact model is embedded into a genetic algorithm as a function. After optimization, the optimized pin fin dimensions are obtained.
Simulation Framework

Phase 1 (timing simulation[^3]): The benchmark is executed on a cycle-based simulator, which collects the info of pipeline execution and cache reference.

Phase 2 (power analysis[^4]): The floor plan and architecture info are used to generate the power traces of different components.

Phase 3 (thermal analysis[^5]): The 3D floor plan and power traces are used as the input of the thermal library to compute the thermal fields, which update the leakage power for the next iteration.


Simulation Framework Cont’

**Convection Heat Sink**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat transfer coefficient</td>
<td>1.2e-11 W/(\mu m^2)K</td>
</tr>
<tr>
<td>Ambient temperature</td>
<td>300 K</td>
</tr>
</tbody>
</table>

**Micro Pin Fin**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pin material</td>
<td>Silicon</td>
</tr>
<tr>
<td>Pin distribution</td>
<td>Staggered</td>
</tr>
<tr>
<td>Coolant vol. heat cap.</td>
<td>4.17e-12 J/(\mu m^3)K</td>
</tr>
<tr>
<td>Coolant incoming temp.</td>
<td>300 K</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DP (um)</th>
<th>PS (um)</th>
<th>HP (um)</th>
</tr>
</thead>
<tbody>
<tr>
<td>baseline</td>
<td>100</td>
<td>200</td>
</tr>
<tr>
<td>optimized</td>
<td>180</td>
<td>320</td>
</tr>
</tbody>
</table>

*DP: diameter, PS: pitch spacing, HP: height; Pumping power 0.03W*

The system monitor is built inside the simulator to coordinate the execution of timing model and the invocation of the physical models across sampling windows.
leakage is more significant

The pin fin is fixed to baseline configuration with input velocity 0.3m/s
**Case Study**

- **Barnes:** (computational-bounded) simulates the interaction of a system of bodies in three dimensions using Barnes-Hug hierarchical N-body method.

- **Ocean-c:** (Memory-bounded) studies large-scale ocean movements based on eddy and boundary currents, using a red-black Gauss-Seidel multigrid equation solver.

<table>
<thead>
<tr>
<th></th>
<th>Time</th>
<th>Space</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Barnes</strong></td>
<td>NlogN</td>
<td>N</td>
</tr>
<tr>
<td><strong>Ocean-c</strong></td>
<td>N^3</td>
<td>N^2</td>
</tr>
</tbody>
</table>
Leakage Characterization

![Graph showing leakage characterization with various markers indicating different points.]

- **Sat. Pt.**
- **Barnes**
- **Ocean-c**

4.75X

3.31X

1.79X

1.39X
Performance Speedup and Energy Efficiency

Clock scaling improves overall 20% and 40% performance in 4GHz and 5GHz respectively.

- Barnes benefits more than ocean-c because of lower miss rate and fewer memory interaction

- Barnes suffers from 2X degradation in EPI
- Ocean has a roughly constant EPI
- The results overestimate the power as we still use the 16nm model from ITRS 2007.

EPI degradation is detected due to the exponential relationship between leakage, temperature and supply voltage.

- Barnes suffers from 2X degradation in EPI
- Ocean has a roughly constant EPI
- The results overestimate the power as we still use the 16nm model from ITRS 2007.
Conclusion

- The saturation point of coolant velocity is determined by the pin fin geometry, system frequency and runtime application. A typical saturation value for system within 5GHz is 0.4 m/s.

- Barnes saves 37.2% and 33.9% leakage power respectively for the baseline and optimized system running at 5GHz with input velocity from 0.1 m/s to 0.8m/s, compared to ocean-c 18.3% and 13.2%.

- The optimized pin fin can save up to 20% leakage dissipation with a same pumping power.

- The energy efficiency tends to increase with frequency for applications running at low temperatures (i.e. below 335K), as the performance speedup will compensate the increase of power.
Thank You Questions?