High Performance Closed-Channel Cooling System Using Multi-channel Electro-osmotic Flow pumps for 3D-ICs

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Outline of Presentation

• Closed-channel cooling system
• Multi-channel EOF pumps
• Cooling chip fabrication
• Pumping performance
• Cooling capability
Power Density of MPUs

Power density (W/cm²)

- Hot spot
- Average power density

Technology node

45nm 32nm 22nm 14nm 10nm

Power density (W/cm²)

0 50 100 150 200 250 300

x 3
Hot Spot Issues

• Lowering of speed performance
• Increase in power consumption
• Degradation of functional reliabilities
• Thermal management for 3D-IC integration
Typical Micro-channel Cooling System

- MPU
- External heat exchanger
- Micro-channel heat sink
- Outer pump
- Micro-channels

[Diagram of a typical micro-channel cooling system with labeled components: MPU, external heat exchanger, micro-channel heat sink, outer pump, and micro-channels.]
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Closed-channel Cooling System (C³S)

- Gas-liquid phase coolant
- Liquid phase coolant
- Heat removal region
- Hot spot
- 3D-IC
Application of C³S to 3D-IC

Closed-Channel Cooling System

MPU/GPU

Wide IO DRAM

on-chip TSVs

PCB or Interposer

Off-chip TSVs
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Electro-osmotic Flow (EOF) Mechanism

Flow rate = \(-\frac{\varepsilon \zeta w D}{\mu} E\) - \(\frac{w D^3}{12\mu} \frac{\Delta P}{L}\)
Multi-channel EOF pumps

- Applied voltage
- Ground status
- Ti electrode
- Si-trench
- Flow direction

$D_1: 5 \mu m$
$L_1: 50 \mu m$
$L_2: 100-200 \mu m$

$D_2: 100 \mu m$

Ti electrode
Si-trench

- Applied voltage
- Ground status
## Dimensions of EOF pump

<table>
<thead>
<tr>
<th>Chip</th>
<th>Channel-A</th>
<th>Channel-B</th>
<th>Channel-C</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_1$ (µm)</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>$D_2$ (µm)</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>$L_1$ (µm)</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>$L_2$ (µm)</td>
<td>100</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Channel (EOF unit) number</td>
<td>91</td>
<td>55</td>
<td>46</td>
</tr>
</tbody>
</table>
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Fabrication Process of Cooling Chip

(a) Si trench formation

(b) Formation of through Si via (TSV) filled with electro-plated Cu

(c) Patterning Al line for applying voltage
(d) Patterning of Ti electrode for EOF pumps

(e) Surface activated bonding (SAB)
Filled Cu lines to apply voltage

Bonded interface

Electrodes

Si trench

Al lines

Filled Cu

Ti electrode

In-process SEM photos

Si trench from tilt angle

TSV filled with electro-plated Cu
Close-up Images of EOF pumps and Hot Spot

- EOF pumps
- Hot spot
- Cooling chip
- Bottom of Si trench
- Ti electrode
- Fluid channel
- Flow direction
- Ti heater
- 100 μm
- 500 μm
Cooling Chip Mounted to Measurement Jig

Wires for applying voltage

Cooling chip

Inlet  Outlet

Coolant: Isopropyl alcohol (IPA)
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$P_{\text{max}}$ and $Q_{\text{max}}$ as a Function of Number of EOF Unit at 40 V
Normalized $P_{\text{max}}$ and $Q_{\text{max}}$ by Total Channel Area

Channel: $L_1/L_2/n$
- A: 50/100/91
- B: 50/200/55
- C: 50/200/46

$P_{\text{max}}/S (k\text{ Pa/cm}^2)$ vs. Applied voltage (V)

$Q_{\text{max}}/S (\mu\text{l/min.cm}^2)$ vs. Applied voltage (V)
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Fluid Behavior of Coolant on Hot Spot

Evaporated coolant

Hot spot (0.5x2.0mm)

Flow direction
Change in Coolant Temperature at Back and Front Sides of Hot Spot

- Temperature (°C)
- Time (sec.)

- Back side
- Front side

Hot spot
EOF pumps on

- Hot spot on
- Front side
- Back side
Summary

• We have successfully fabricated a cooling chip equipped with C³S with multi-channel EOF pumps.

• Operating the EOF pumps with a very low applied voltage of 40 V.

• High pumping capability: \( P_{\text{max}} = 10 \text{ kPa}, Q_{\text{max}} = 38 \mu\text{l/min} \).

• Cooling capability was as high as 140 W/cm².

• C³S with the EOF pumps enable us to meet the requirements of 3D-ICs.
Acknowledgements

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