Self-adaptive microvalve array for energy efficient fluidic cooling in microelectronic systems

Hassan Azarkish, Louis-Michel Collin, Luc G. Frechette
(Universite de Sherbrooke, Quebec, Canada)
Jerome Barrau (Universitat de Lleida, Lleida, Spain)
Perceval Coudrain (STMicroelectronics, France)
Guillaume Savelli (CEA-Liten)

STREAMS
Smart Technologies for eneRgy Efficient Active cooling in Advanced Microelectronic Systems

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Introduction and motivations

• To reach higher microelectronic performances, heat management is nowadays a major challenge

• Present microchannel cooling solutions
  • Chip embedment microchannels: best solution, but not always possible or easy (e.g. for expansive and complex chips)
  • Uniform channels/pin fins: non-uniform cooling + extra pumping power
  • Layout specific cooling (hot spot management): requires considerable design resources

• Proposed solution

  “To manage the chip heat from an interposer, by avoiding both layout specific or uniform cooling solutions”
STREAMS objectives

• Global project objective
  • To implement a **self-adaptive** (time and space) microfluidic cooling system
  • To minimize the overall **pumping power** dedicated to coolant
  • To increase the surface **temperature uniformity** of the interposer

Requires a smart distribution management
Design approach

The interposer is divided into pixels

Each pixel has a heat exchanger (cell) with a single inlet and outlet

Contains convection enhancing structures

Pixel array on the interposer with an arbitrary heat flux distribution
(Pixel dimensions: 1 mm * 1.2 mm)

Thermoactivated microvalves controlling the cell flow rates for temperature regulation

Clamped-clamped metal beam over a slot

Valves experimentally tested

Source: McArthy et al. [2007]

The cooling is managed by an array of thermoregulated valves
Advantages

Flow rate locally controlled based on temperatures
- Reduces pumping power by limiting the flow rate to the required areas only
- Increases the interposer and chip temperature uniformity

Short microstructure length
- The steam only crosses a short length in the cell microstructures: the corresponding pressure drop is significantly lower than with conventional microchannels

Cold coolant for inlets
- Each cell is individually feed by a non-heated coolant
- Unlike conventional microchannels, it is independent of the hot spot position along the steam

Compatibility and flexibility
- Can manage heat layout modification in time and space
- The adaptive property is passive
- No need to design for hot spot layout adaptation
Modeling

• Properties
  • 2D conduction in lateral direction
  • Uniform temperature per cell
  • Flow rates for each cell: function of the cell temperature

• Model

Pixel array modeling

Heat fluxes in a pixel

Microvalve temperature response

- Linear: \( \dot{m} = a + bT \)
- Quadratic: \( \dot{m} = a + bT^2 \)
- Exponential: \( \dot{m} = a \exp(bT) \)

Three microvalves behaviors analysed
Case studies

Cooling properties
- Pixel array: 16 rows and 20 columns (320 pixels)
- Pixel size: $L_p=1200 \, \mu m$, $W_p=1000 \, \mu m$, $H_d=300 \, \mu m$
- Maximum allowed temperature: 100 °C
- Total heat load 38.8 W

Heat source scenarios
1) Thermal map with non-uniform hotspots
2) Thermal map with uniform hotspots
3) Uniform heat flux (without hotspots)

Considered case studies
1) Without microvalve
2) Single global microvalve
3) A linear microvalve per pixel
4) A quadratic microvalve per pixel
5) An exponential microvalve per pixel

The first studied case: the thermal map with non-uniform hotspots is analysed
Temperature distribution for non-uniform hotspots

1) Without microvalve
- Overcooling ($T_{\text{max}} << 100^\circ\text{C}$)
- High temperature non-uniformity (~20$^\circ\text{C}$)
- Conclusion: Not efficient

2) One global microvalve
- 51% flow rate reduction over case 1
- High temperature non-uniformity (>20$^\circ\text{C}$)

3) A linear microvalve per pixel
- ~39% temperature non-uniformity reduction over case 2
- Similar flow rate to case 2

4) A quadratic microvalve per pixel
- ~39% temperature non-uniformity reduction over case 2
- Similar flow rate to case 2

5) An exponential microvalve per pixel
- The most uniform temperature
- Slightly higher flow rate than cases 3 and 4
Microvalves behavior

<table>
<thead>
<tr>
<th></th>
<th>1 Without microvalve</th>
<th>2 Single microvalve</th>
<th>3 Set of linear microvalves</th>
<th>4 Set of quadratic microvalves</th>
<th>5 Set of exponential microvalves</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total mass flow rate (mg/s)</td>
<td>320</td>
<td>158</td>
<td>160</td>
<td>160</td>
<td>176</td>
</tr>
<tr>
<td>Maximum temperature differences (°C)</td>
<td>20.1</td>
<td>22.8</td>
<td>14.2</td>
<td>13.8</td>
<td>9</td>
</tr>
<tr>
<td>Maximum temperature (°C)</td>
<td>69.7</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

Analysis

- A regulation valve is required for
  - Proper use of pumping power
  - Having a decent temperature uniformity

- Linear and quadratic valves offers similar performances

- Compared to a single microvalve, the exponential microvalve reduces the temperature non-uniformity of 60.5 % with an increase of only 11.4 % in flow rate
Mass flow rate distribution

Linear microvalve per pixel (similar for quadratic microvalve)

Exponential microvalve per pixel

Flow rate

Temperature

Flow rate

Temperature

Microvalves with the highest flow rates variations have the most temperature uniformity
Microvalves behavior

• **Investigation**
  - Flow rate distribution is compared in a row of pixels for the different configurations
  - Colored bars represents heat source injections

• **Results**
  - **Lateral thermal conductivity:** limits the thermal spreading
  - **Exponential microvalve arrays:**
    - More temperature sensitive
    - Produces a better temperature uniformity
  - **Single microvalve vs arrays of microvalves:** no significant change the overall flow rate
  - **Microvalve arrays:** increases the temperature uniformity (due to the thermal resistance modulation for each pixel)
Effect of heat flux map

Uniform hot spots

• Similar flow rates compared to the non-uniform hot spots case (slight decrease)
• Heat source distribution has a significant effect on the chip temperature uniformity

Uniform heat flux

• Completely uniform interposer temperature (not the case with uniform microchannels)
Conclusions

Cell arrays: better cooling uniformity with a uniform heat flux

Global flow rate: minimized by using a single microvalve or a set of microvalves

Temperature-regulated microvalves: allow a local control

The microvalve arrays: have significant effect on the chip temperature uniformity

Exponential microvalve array: provides the most uniform chip surface temperature
Acknowledgments

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Thank you for your attention