TSV-Constrained Micro-Channel Infrastructure Design for Cooling Stacked 3D-ICs

Bing Shi and Ankur Srivastava

University of Maryland
Motivation of active cooling

- Three dimensional circuits (3D-IC)
  - Several vertically stacked layers
  - High power density
  - Thermal issue in 3D-IC: Micro-channel based interlayer liquid cooling
Related work in micro-channel cooling for 3D-ICs

- **Thermal and hydraulic modeling of micro-channel**
  - [Koo et al, JHT’05], [Kim et al, JHT’10], [Sridhar et al, ICCAD’10], [Mizunuma et al, ICCAD’09]

- **Micro-channel optimization**
  - shape optimization for straight rectangular channel
    - [Tuckerman et al, EDL’81], [Knight et al, CHMT’92]
  - complex micro-channel structures
    - [Jiang et al, IMECE’02], [Marques], [Senn et al, JPS’04]
  - Hotspot optimized micro-channel design
    - [Shi et al, DAC’11]

- **DTM using micro-channel**
  - dynamic thermal management with flow rate control
    - [Coskun et al, DATE’10]
Micro-channel design considerations

• Conventional micro-channel structure:
  • straight channel
  • spread channels all over
• Presence of TSVs
• Variation in power/thermal profiles
Straight channel vs bended channel

- Our previous work: hotspot optimized micro-channel
- Straight channel vs bended channel
Key idea and design objective

- Methodology of designing TSV-constrained micro-channel infrastructure
- Micro-channels with bends
- Better coverage of hotspot
- Save cooling power
Thermal and hydraulic modeling

- Thermal modeling: conduction, convection, fluid flow

\[ R_{\text{conv}} = \frac{1}{hA} = \frac{w_a w_b}{N_u K_f \Delta z (w_a + w_b)^2} \]

\[ R_{\text{heat}} = \frac{1}{C_p \rho f} \]
Thermal and hydraulic modeling

• Pumping power:

\[ Q_{pump} = \sum_{n=1}^{N} f_n \Delta p_n \]

- Straight channel (fully developed laminar)

\[ \Delta p_n = \frac{2\gamma\mu L}{D_h w_a w_b} f_n \]

\[ Q_{pump} = \sum_{n=1}^{N} \frac{w_a w_b D_h^2}{2\gamma\mu L} \Delta p_n^2 \]

- Bended channel:
  - Fully developed laminar region
  - Corner region

\[ \Delta P_{90^\circ} = m \Delta p_{90^\circ} = m\frac{\rho}{2}K_{90}v^2 \]

- Flow developing region

\[ \Delta P_d = m \Delta p_d = mK_d\rho v^2 \]
Micro-channel structure design-problem formulation

• Given:
  ▫ 3D-IC structure
  ▫ TSV locations
  ▫ Power profile
  ▫ Inlet and outlet orifices of micro-channels

• Decide the structure of micro-channels
Micro-channel structure design - initial design

Using min-cost flow based approach

Node capacity: 1
Node cost: $\propto \frac{1}{\text{cooling demand}}$
Iterative micro-channel improvement

Workload balancing

Unbalanced cooling demand

Bend elimination

Different number of bends
Performance of bended micro-channel vs straight micro-channel structure

46% cooling power saving on average
Resulting micro-channel structure

Initial design  After workload balancing  After bend elimination
Thank you!

Questions?