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

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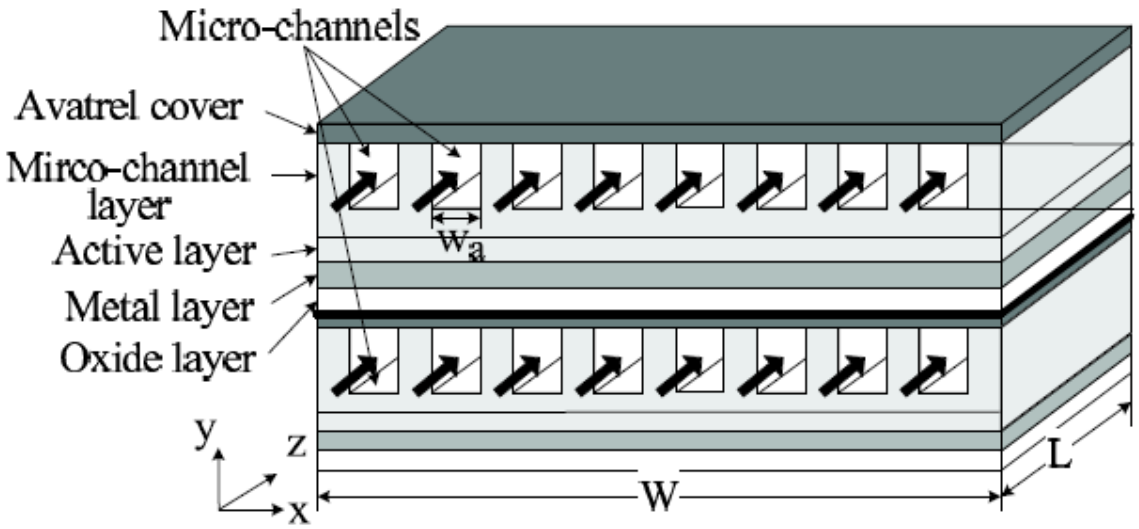
Motivation of active cooling

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

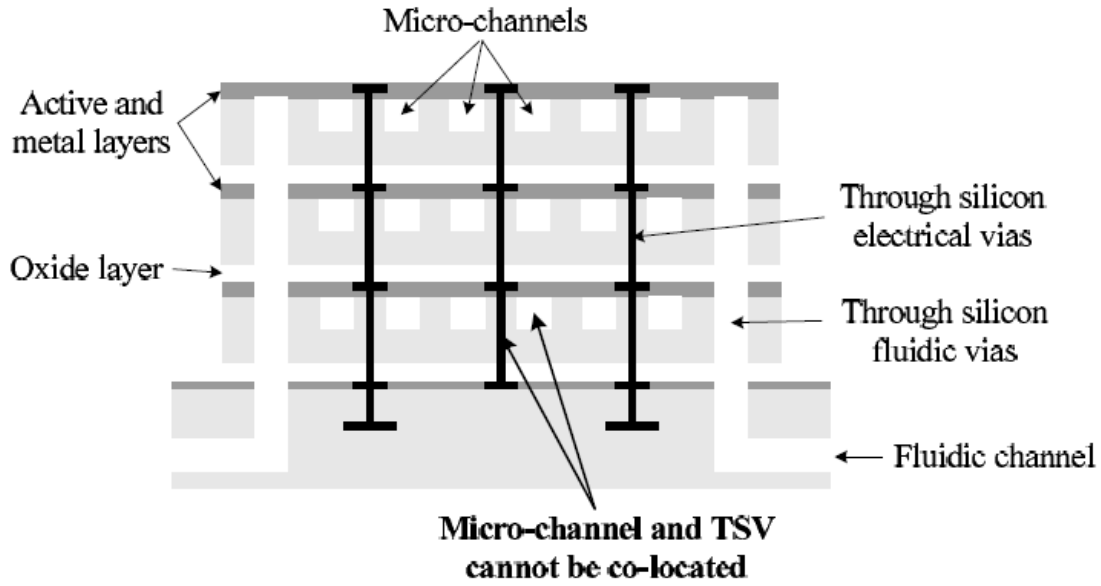


Related work in micro-channel cooling for 3D-ICs

- 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]

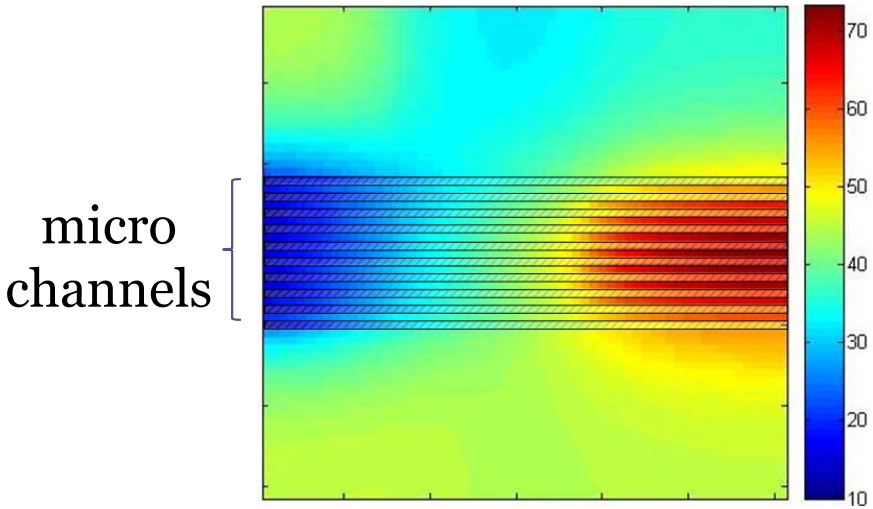
Micro-channel design considerations

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

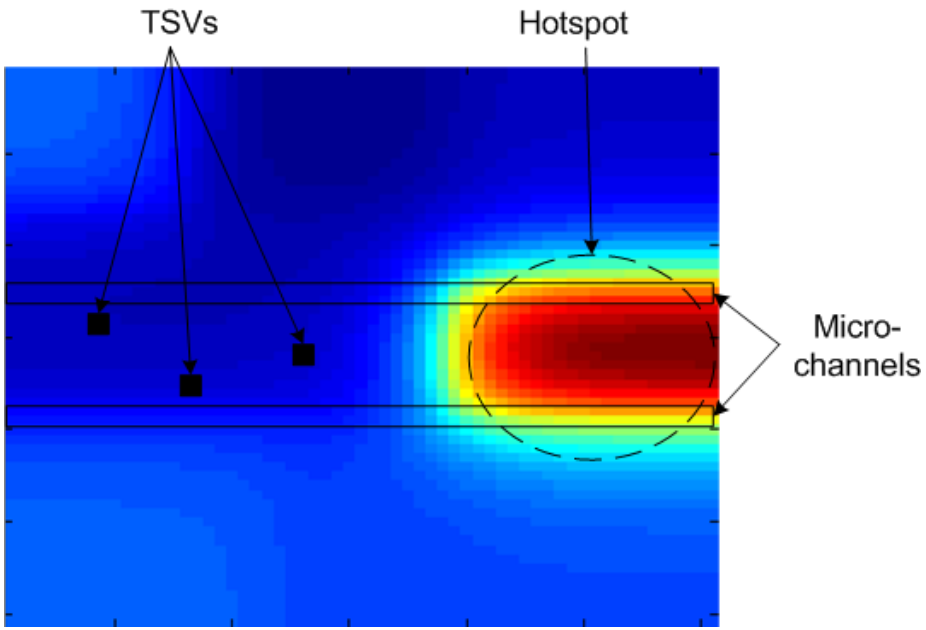


Straight channel vs bended channel

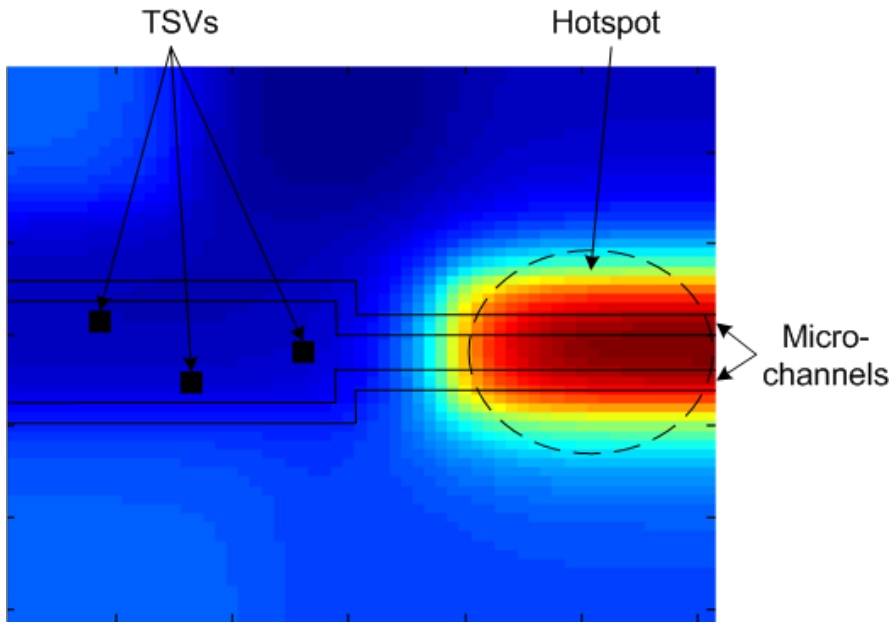
- Our previous work: hotspot optimized micro-channel
- Straight channel vs bended channel



Straight channel



Bended channel

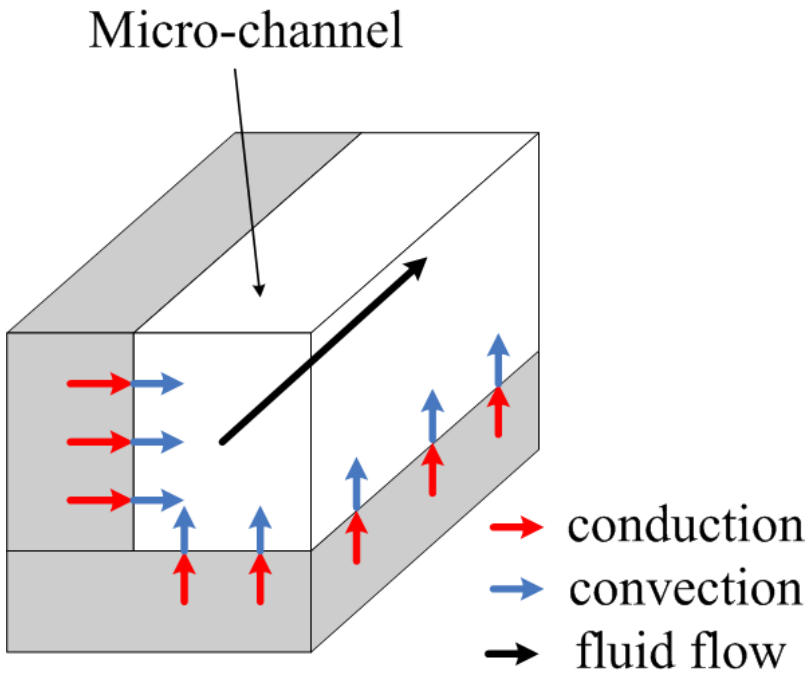


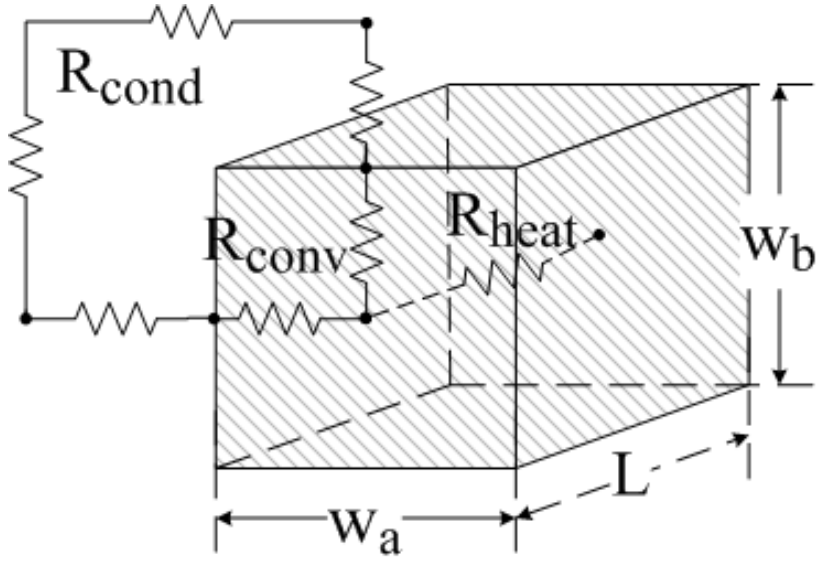
Key idea and design objective

- 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

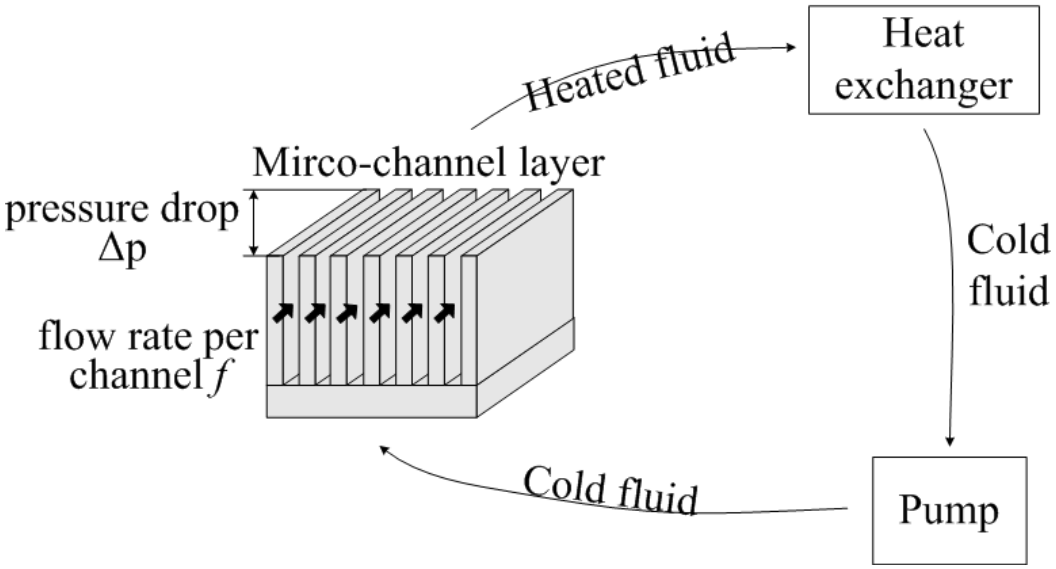


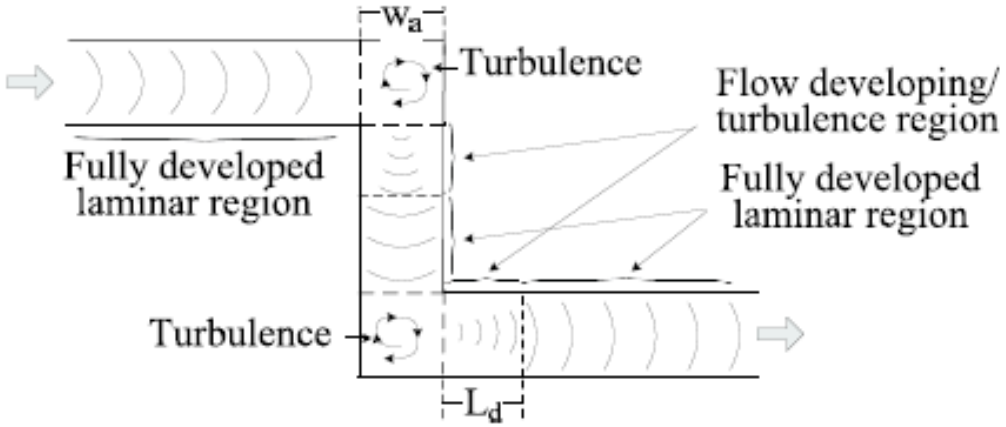


$$R_{conv} = 1/hA = \frac{w_a w_b}{N_u K_f \Delta z (w_a + w_b)^2}$$

$$R_{heat} = \frac{1}{C_p \rho f}$$

Thermal and hydraulic modeling





- Pumping power:

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

- Straight channel (fully developed laminar)

$$\Delta p_n = \frac{2\gamma\mu L}{D_h^2 w_a w_b} f_n$$

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

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

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

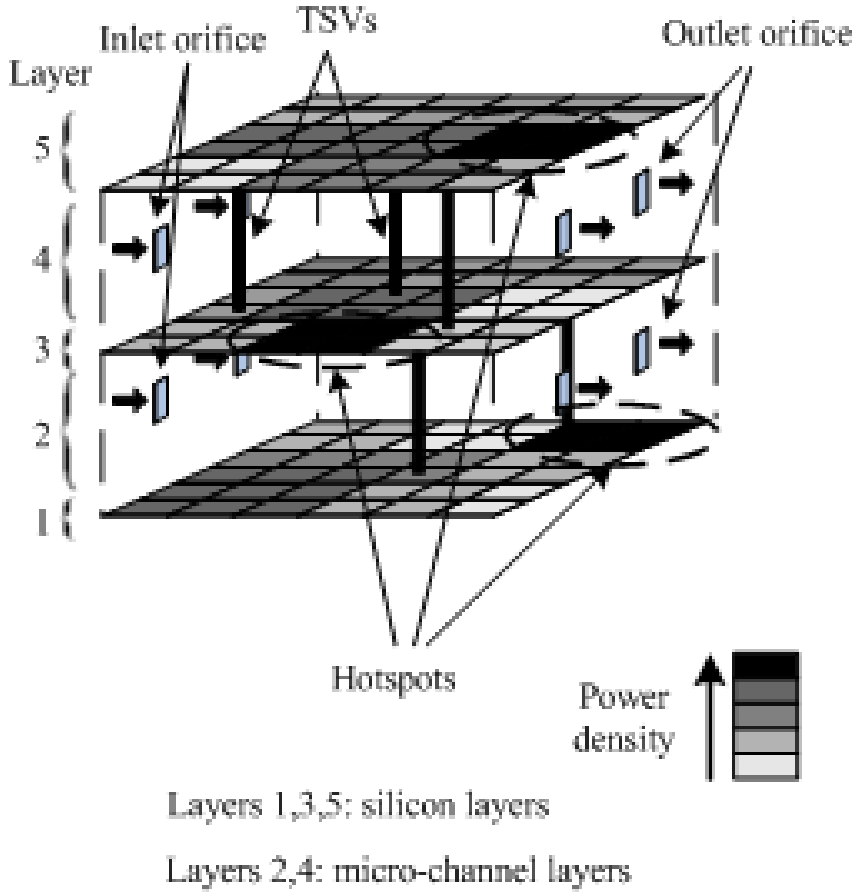
  - Flow developing region

$$\Delta P_d = m\Delta p_d = m K_d \rho v^2$$

Micro-channel structure design-problem formulation

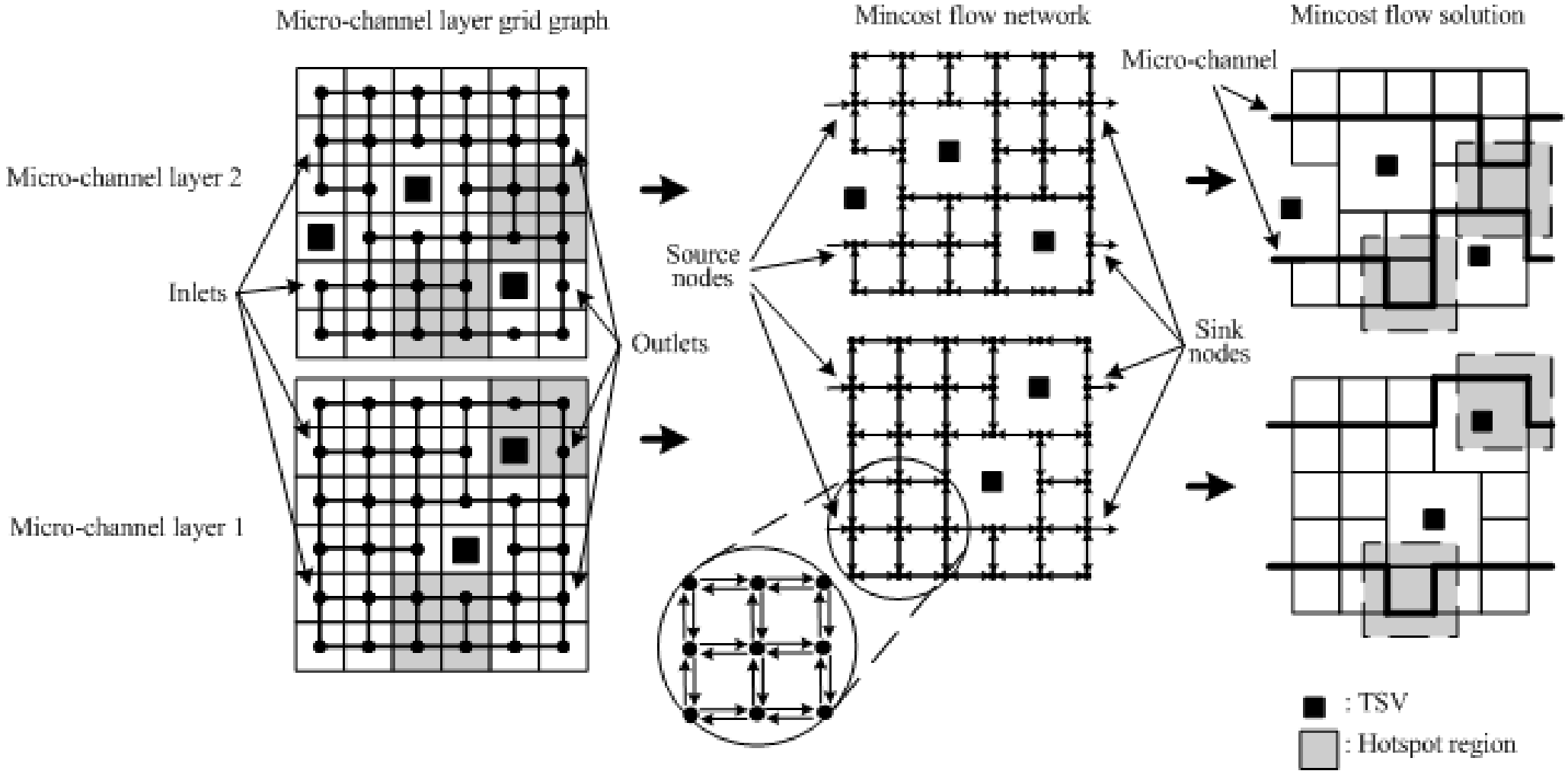
- Given:
  - 3D-IC structure
  - TSV locations
  - Power profile
  - Inlet and outlet orifices of micro-channels

- Decide the structure of micro-channels



Micro-channel structure design – initial design

Using min-cost flow based approach



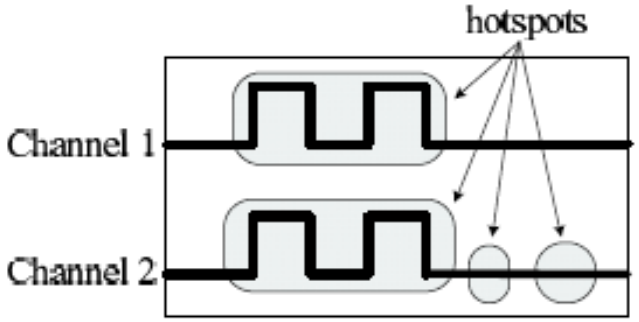
Node capacity: 1

Node cost: $\propto 1/(\text{cooling demand})$

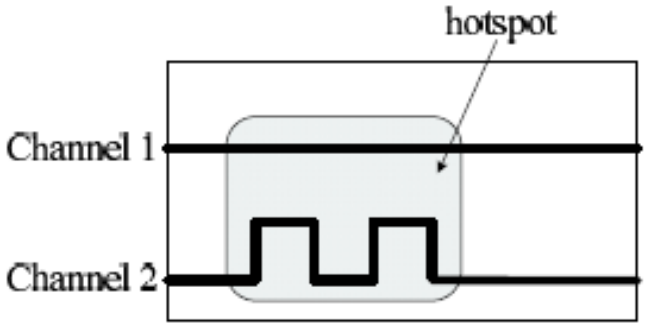
Iterative micro-channel improvement

Workload balancing

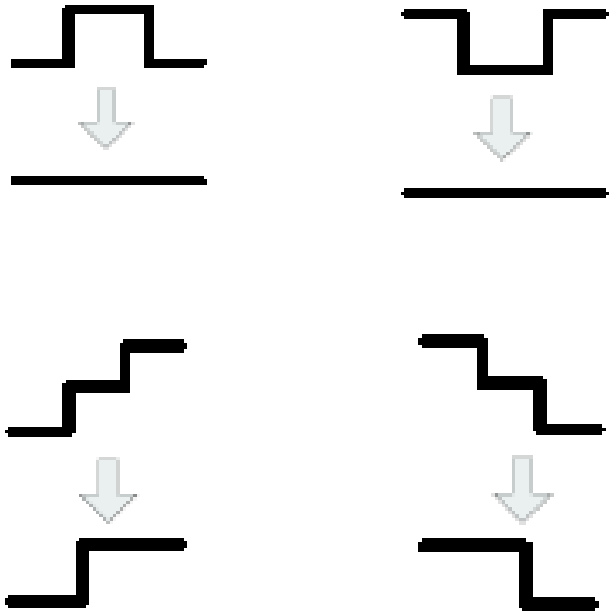
Unbalanced cooling demand



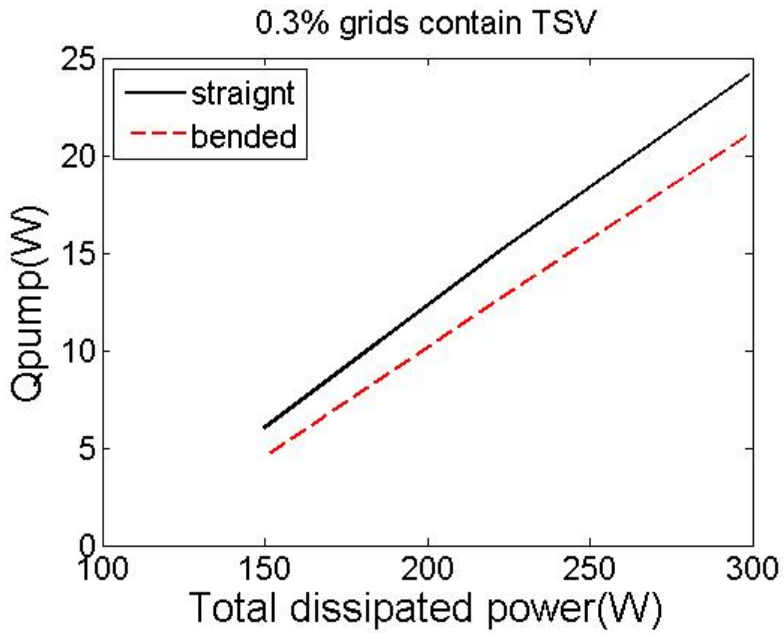
Different number of bends

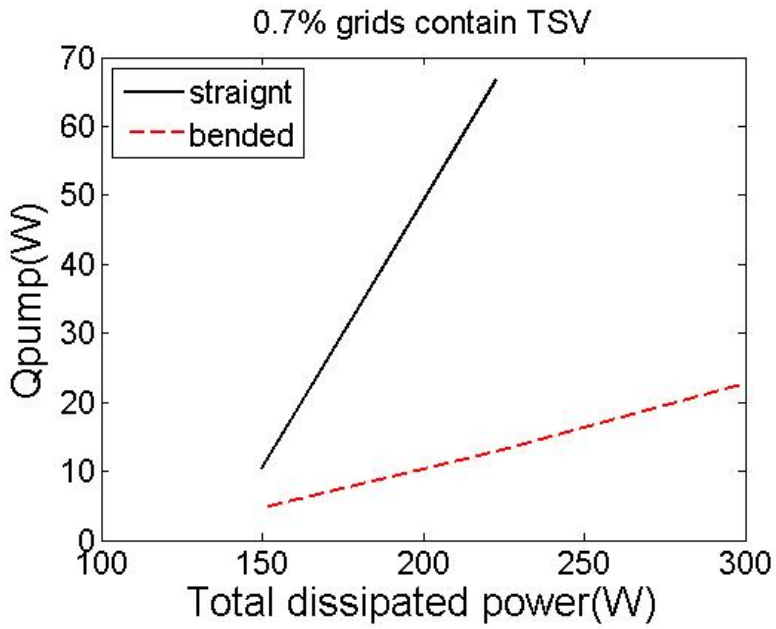


Bend elimination



Performance of bended micro-channel vs straight micro-channel structure





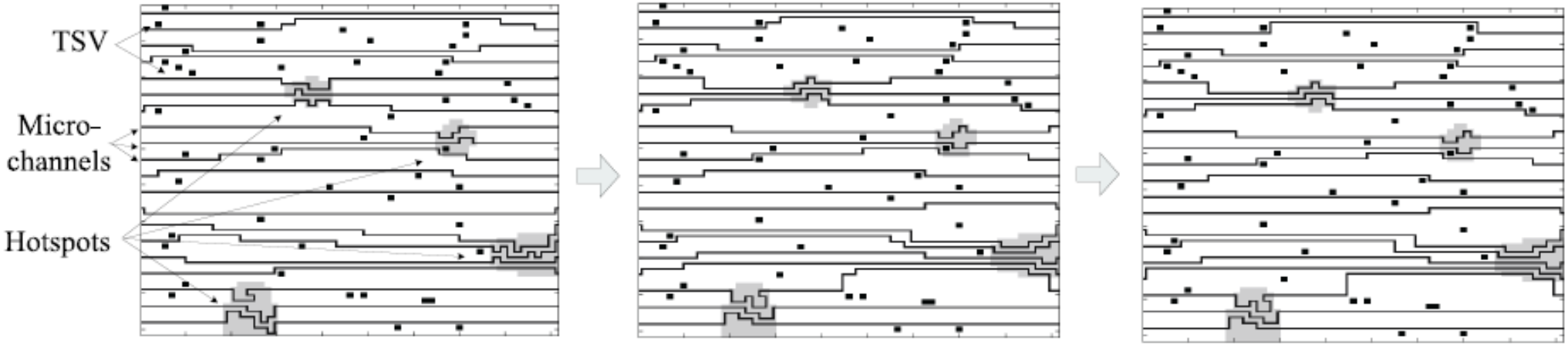
46% cooling power saving on average

Resulting micro-channel structure

Initial design

After workload balancing

After bend elimination



Thank you !
Questions?