Minimizing Thermal Gradient and Pumping Power in 3D IC Liquid Cooling Network Design

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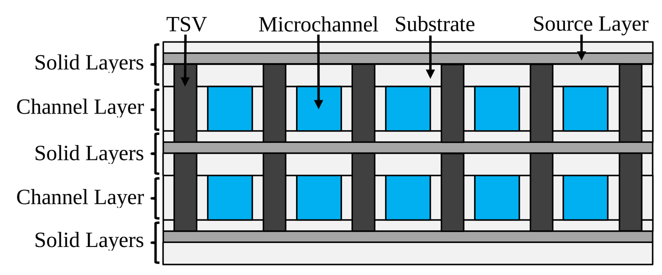
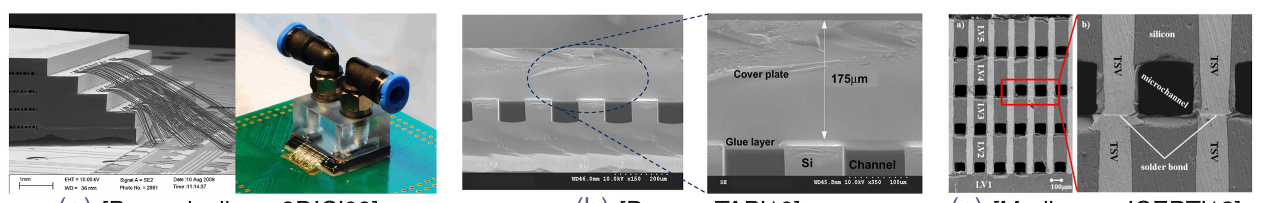
Introduction

Why 3D IC Liquid Cooling?

- **Power** is the number one problem in chip design
- **3D IC** is promising for increasing computer performance
- But 3D IC **worsens** power problem by
  - higher heat dissipation density
  - larger thermal resistance from junction to ambient
- Microchannel-based liquid cooling is proposed as a solution

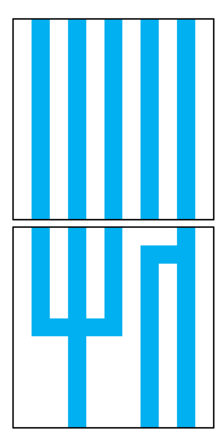




(a) [Brunschwiler+, 3DIC'09] (b) [Dang+, TAP'10] (c) [Madhour+, ICEPT'12]

Challenges for 3D IC Liquid Cooling

- Hot downstream and cool upstream $\Longrightarrow$ **large thermal gradient** $\Longrightarrow$ reliability and timing issues
- limited channel diameter $\Longrightarrow$ **high pumping requirement** $\Longrightarrow$ overhead to whole system
- Limitations of previous work
  - No considering thermal gradient
  - Assuming unidirectional straight channels
  - Assuming unrealistic constant-temperature heat source

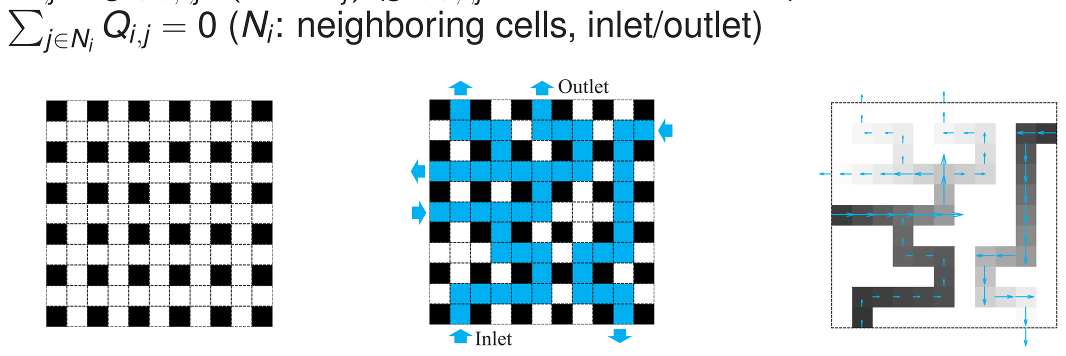


Thermal Modeling

- Most existing models assume unidirectional straight channels
- 4-register model (4RM) in 3D-ICE [Sridhar+, TOC'14]
  - Accurate
  - Has been extended for flexible topology
  - **Slow**
- We construct a fast 2-register model (2RM) for cooling network

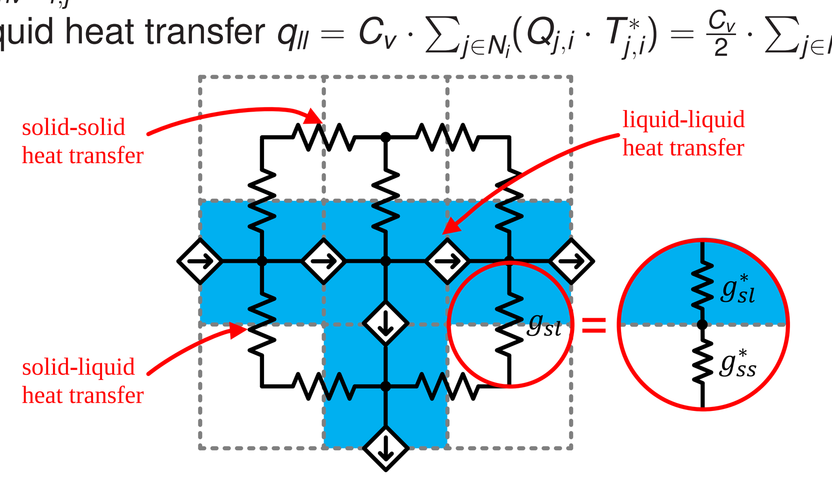
Basics

- Divide channel layer into **basic cells** with a 2D grid
  - Either solid (white/black, black reserved for TSV) or liquid (blue)
- Solve local pressure P_i and flow rate $Q_{i,j}$ from a **linear system**
  - $Q_{i,j} = g_{fluid,i,j} \cdot (P_i - P_j)$ ($g_{fluid,i,j}$: fluid conductance)
  - $\sum_{j \in N_i} Q_{i,j} = 0$ (N_i: neighboring cells, inlet/outlet)



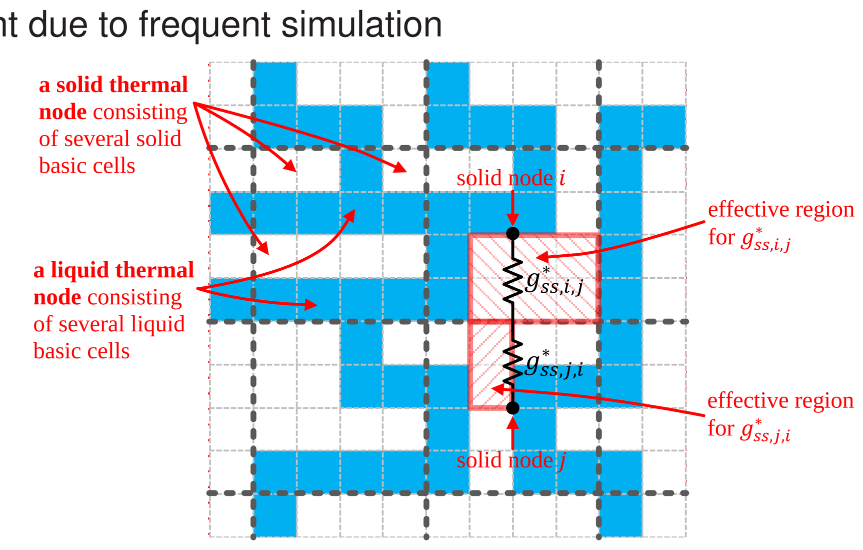
4RM Model

- **Thermal cell** $=$ basic cell
- Solve temperature from a **linear system** considering three kinds of heat transfer
  - Solid-solid thermal conductance $g_{ss} = \frac{q_{i,j}}{T_i - T_j} = \frac{k_{solid} \cdot A_{i,j}}{l_{i,j}}$
  - Solid-liquid thermal conductance $g_{sl} = \frac{q_{i,j}}{T_i - T_j} = g^*_{sl} \parallel g^*_{ss} = \frac{g^*_{sl} \cdot g^*_{ss}}{g^*_{sl} + g^*_{ss}}$ with $g^*_{sl} = h_{conv} A_{i,j}$
  - Liquid-liquid heat transfer $q_{ll} = C_v \cdot \sum_{j \in N_i} (Q_{j,i} \cdot T^*_{j,i}) = \frac{C_v}{2} \cdot \sum_{j \in N_i} (Q_{j,i} \cdot T_j)$



Faster 2RM Model

- No conforming channel geometry $\Longrightarrow$ **larger** and fewer thermal cells $\Longrightarrow$ **speed-up**
- Important due to frequent simulation



Thermal nodes

- In solid layers, $m \times m$ basic cells $=$ a thermal node
- In channel layers, $m \times m$ basic cells $=$ a solid thermal node $+$ a liquid one

Heat transfer

- Solid-solid: only consider complete conducting paths
- Solid-liquid: project horizontal heat transfer to vertical direction
- Liquid-liquid: sum heat transfer over multiple channel connections

Problem Formulations

Decision variables

- **Cooling network topology N**
- **System pressure drop P_{sys}**

Metrics

- **Pumping power** $W_{pump} = \frac{P_{sys} \cdot Q_{sys}}{\eta}$
  - Q_{sys}: system flow rate; η: efficiency term
- **Thermal gradient** $\Delta T = \max_i(\Delta T_i)$
  - ΔT_i: range of node temperatures in i-th source layer
- **Peak temperature** T_{max}

Design Rules

- TSV positions are at alternating basic cells in both dimensions
- Inlets and outlets can only occur at edges of channel layer
- At most one "continuous" inlet and outlet on each side

Problem 1: Pumping Power Minimization

$$\min W_{pump}, \quad \text{s.t. } P_{sys} \in \mathbb{R}^+,\ N \in \mathcal{N},\ T_{max} \leq T^*_{max},\ \Delta T \leq \Delta T^*. \tag{1}$$

($\mathcal{N}$ is the set of all legal cooling networks)

Problem 2: Thermal Gradient Minimization

$$\min \Delta T, \quad \text{s.t. } P_{sys} \in \mathbb{R}^+,\ N \in \mathcal{N},\ T_{max} \leq T^*_{max},\ W_{pump} \leq W^*_{pump}. \tag{2}$$

General considerations

ΔT is most difficult to handle among all metrics (W_{pump}, ΔT and T_{max})

- W_{pump} vs. T_{max} is a simple trade-off under a specific N
- Liquid cooling alleviates T_{max} and worsens ΔT

Three inducing factors for ΔT

1. Temperature rise of coolant
2. Non-uniform power source distribution
3. Non-uniform channel distribution

Factor 3 can be used to compensate for factors 1 & 2

Pumping Power Minimization

The problem is divided into two levels:

- **Inner**: P_{sys} is varied to minimize W_{pump} for a specific N, which evaluates N
- **Outer**: simulated annealing (SA) searches for a good N

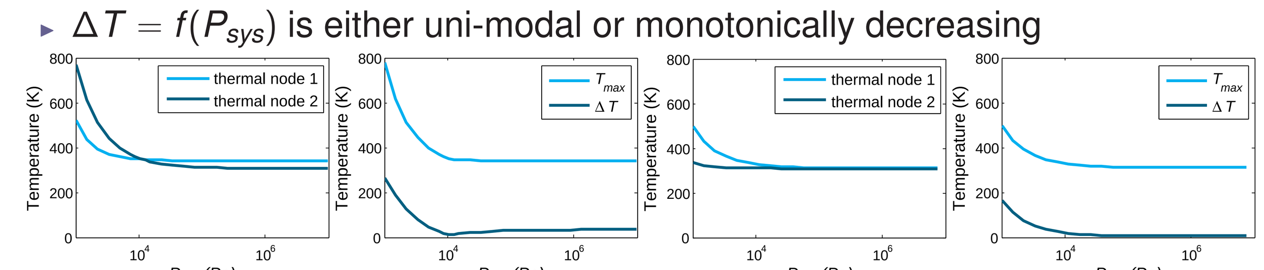
Overall Flow of Pumping Power Minimization

Input: N_{init}, ΔT^*, T^*_{max}, stack description and floorplan files.
Output: N, P_{sys}.

```
1: N ← N_init;
2: while #iteration is within the limit do
3:     Obtain neighboring network solution N';
4:     W'_pump ← EvaluateNetwork (N', ΔT*, T*_max);
5:     N ← N' or not according to SA mechanism;
6:     if W'_pump converges then return N and P_sys;
7: end while
```

Temperature vs. Pressure

- As P_{sys} increases, T_{max} decreases and finally becomes approximately constant
- $\Delta T = f(P_{sys})$ is either uni-modal or monotonically decreasing



Network Evaluation

- Replace W_{pump} by P_{sys}, as W_{pump} vs. P_{sys} is monotonic for a specific N
- Ignore T_{max} first, as it is easier to handle
  - Step 1: solve the problem without constraint T^*_{max}
  - Step 2: check T_{max} and find optimal solution by binary search

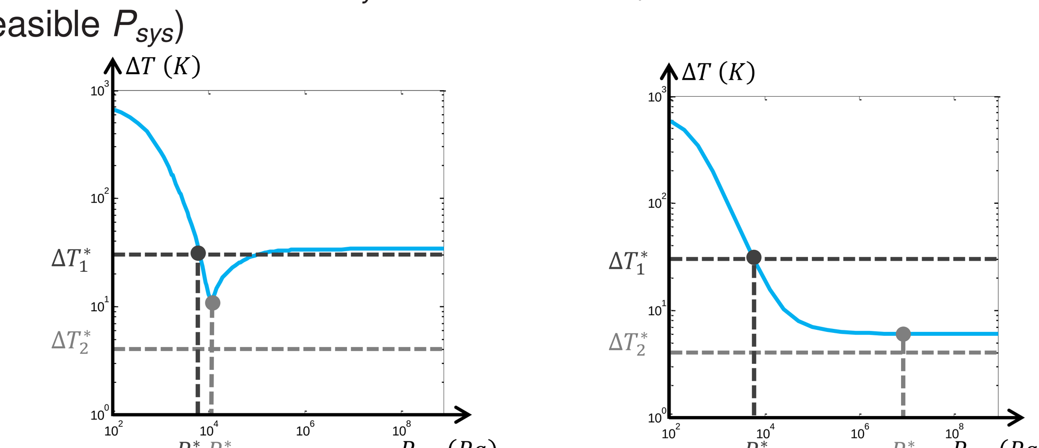
Network Evaluation of Pumping Power Minimization

```
 1: function EvaluateNetwork(N, ΔT*, T*_max)
 2:     Minimize W_pump s.t. ΔT ≤ ΔT*;
 3:     if ΔT > ΔT* then
 4:         return +∞;
 5:     else if T_max > T*_max then
 6:         Minimize W_pump s.t. T_max ≤ T*_max;
 7:         if ΔT > ΔT* or T_max > T*_max then
 8:             return +∞;
 9:         else
10:             return W_pump;
11:         end if
12:     else
13:         return W_pump;
14:     end if
15: end function
```

- In step 1, by further substituting $\Delta T = f(P_{sys})$, Problem 1 becomes single-variable:

$$\min P_{sys}, \quad \text{s.t. } P_{sys} \in \mathbb{R}^+,\ f(P_{sys}) \leq \Delta T^*. \tag{3}$$

- Solve (3) by searching (with three probing points):
  - If a feasible P_{sys} exists, return optimal P_{sys}
  - Otherwise, return the P_{sys} for minimum f (show the nonexistence of feasible P_{sys})

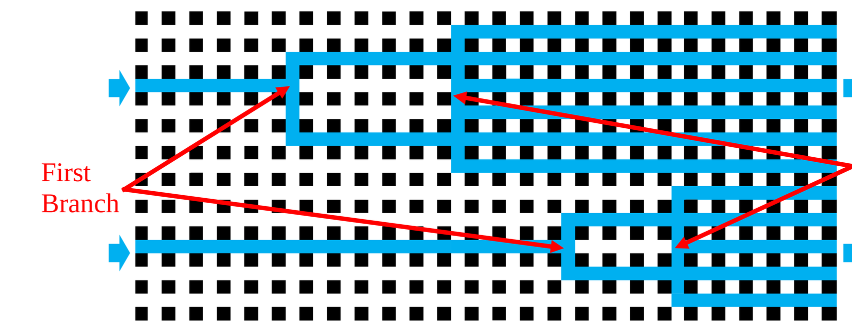


Pumping Power Minimization

Tree-like Cooling Network

Hierarchical tree-like structure is simple and can balance cooling:

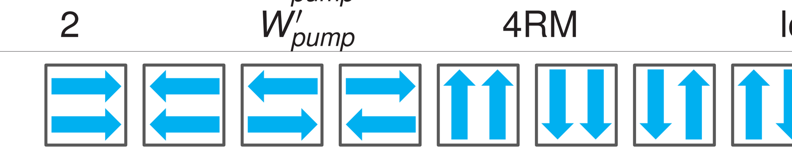
- Between upstream and downstream (factor 1)
- Among different trees (factor 2)



Network Topology Optimization

- In stage 1, ΔT under a **fixed** P_{sys} is used as cost function to accelerate
- In earlier stages, more **rounds** are performed to fully explore solution space
- Eight types of global flow directions are attempted

Stage #	Step Size	Objective Function	Simulator	Runtime for an Iteration
1	10	ΔT	2RM	short
2	10	W'_{pump}	2RM	medium
3	2	W'_{pump}	2RM	medium
4	2	W'_{pump}	4RM	long



Thermal Gradient Minimization

Similar to solving pumping power minimization with some optimization

Network Evaluation

- Its simplified form becomes:

$$\min f(P_{sys}), \quad \text{s.t. } P_{sys} \in \mathbb{R}^+,\ P_{sys} \leq P^*_{sys}. \tag{4}$$

- Solving (4) is simpler:
  - If P^*_{sys} locates on falling side of f, it is optimal already
  - Otherwise, adopt golden section search

Network Topology Optimization

Minimizing W_{pump} under a fixed P_{sys} is unrelated to temperature and meaningless, but minimizing ΔT under a fixed P_{sys} is safe $\Longrightarrow$ **speed-up**

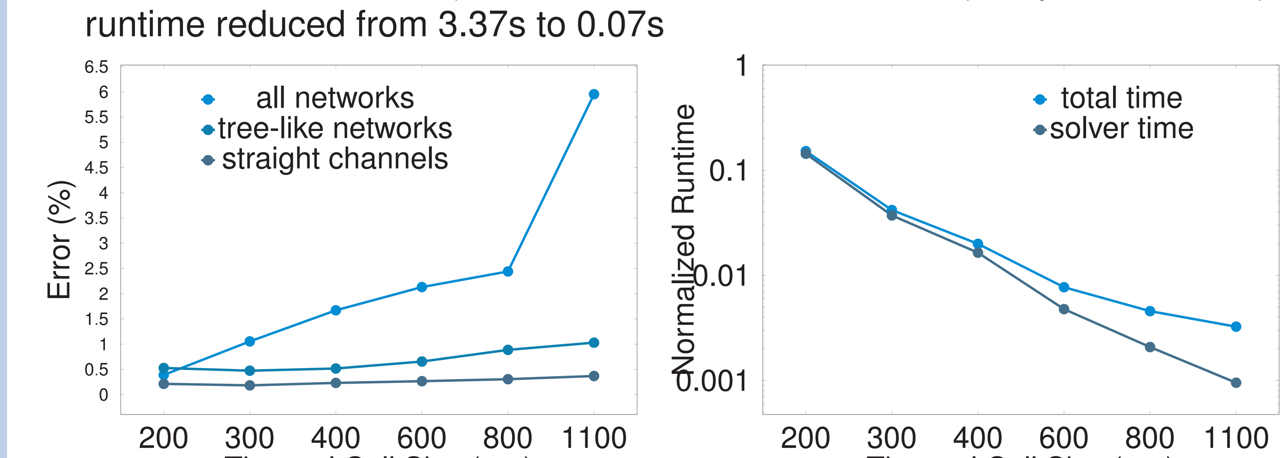
- Some iterations are evaluated by one simulation under a fixed P_{sys}
- The original stage 1 is no longer needed
- Another stage with 4RM is affordable to replace the original stage 3

Stage #	Step Size	Objective Function	Simulator	Runtime for an Iteration
1	10	$\Delta T'$	2RM	short
2	10	$\Delta T'$	4RM	medium
3	2	$\Delta T'$	4RM	medium

Experimental Results

Faster 2RM Model

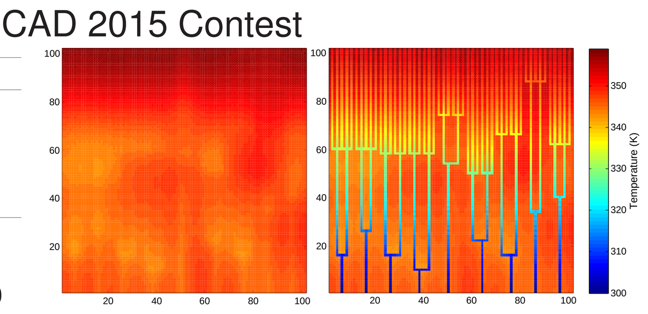
- 5 benchmarks, 40 network samples, 6 thermal cell sizes and 13 pressures
- Tree-like networks, 400μm thermal cells: 0.52% errors (compared to 4RM), runtime reduced from 3.37s to 0.07s



Pumping Power Minimization

- 40 min for cases 1-3 and 240 min for case 4
- **79.61%** better than baseline (unidirectional straight channels)
- **16.35%** better than 1st place in ICCAD 2015 Contest

Case #		1	2	3	4	5
Baseline	P_{sys} (kPa)	12.98	6.23	7.85	9.71	N/A
	T_{max} (K)	322	314	321	314	N/A
	ΔT (K)	15.0	10.0	15.0	10.0	N/A
	W_{pump} (mW)	**10.41**	**6.91**	**8.34**	**11.65**	**N/A**
Manual (1st place in ICCAD Contest)	P_{sys} (kPa)	8.86	5.54	6.98	9.45	40.1
	T_{max} (K)	357	336	328	336	338
	ΔT (K)	15.0	10.0	15.0	10.0	10.0
	W_{pump} (mW)	**1.72**	**1.51**	**3.36**	**2.96**	**113.96**
Ours	P_{sys} (kPa)	8.72	5.13	5.81	8.27	40.10
	P_{system} (kPa)	358	336	337	335	338
	ΔT (K)	15.00	10.0	15.0	10.00	10.00
	W_{pump} (mW)	**1.66**	**1.37**	**1.90**	**2.68**	**113.96**

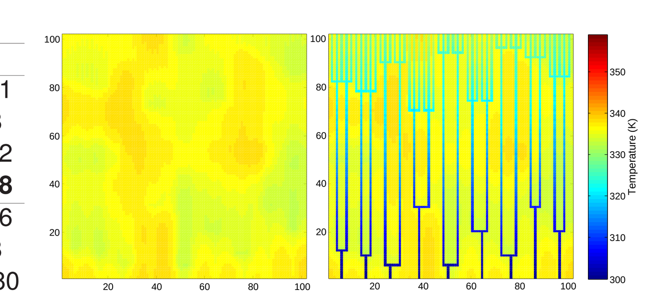


bottom source layer channel layer

Thermal Gradient Minimization

- Constraint W^*_{pump} on W_{pump} is set to 0.1% of die power
- **37.27%** better than baseline

Case #		1	2	3	4	5
Baseline	P_{sys} (kPa)	26.08	14.43	17.82	26.51	45.81
	T_{max} (K)	316	309	316	308	338
	W_{pump} (mW)	42.0	37.0	43.0	43.4	148.2
	ΔT (K)	**8.75**	**5.42**	**11.42**	**4.76**	**26.48**
Ours	P_{sys} (kPa)	16.51	8.96	11.46	13.80	40.06
	T_{max} (K)	338	319	327	321	338
	W_{pump} (mW)	5.67	5.66	6.56	4.16	113.80
	ΔT (K)	**5.54**	**3.81**	**7.12**	**3.87**	**9.64**



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