3D Computer Architectures: Two-Phase Interlayer Cooling

“Swiss Nano-Tera CMOSAIC Project”

Prof. John R. Thome
Project PI

Director: Laboratory of Heat and Mass Transfer
Ecole Polytechnique Fédérale de Lausanne
EPFL-STI-IGM-LTCM, Mail 9,
CH-1015 Lausanne, Switzerland

MEPTEC, San Jose, CA: March 19, 2012
Two-Phase Cooling of 3D Stacked Microprocessors

3D integration & thermal management

3D integration opportunities & threats

- Global wire length reduction
- Memory-on-core stacking with vertical electrical communication → massive core-to-cache bandwidth
- Shorter wires & no repeaters → improved power efficiency
- Threats: heat flux accumulation, additional thermal resistances, peak temperatures

Vertical electrical interconnect: Through-Silicon-Via (TSV)

How to remove heat from a chip stack: interlayer cooling

- Scales with number of dies whereas backside cooling scales only with die area
- Heat removal: refrigerant two-phase cooling
- Two-phase: no electrical insulation, minimal temperature gradients, automatic hot-spot heat removal BUT dry-out problem, complex system
TWO-PHASE FLOW COOLING ADVANTAGES

• High latent heat of vaporisation (~150kJ/kg).
• Low mass flow required (low energy consumption/green operation).
• Refrigerants are dielectric fluids and clean.
• Cooling up to 200-300 W/cm$^2$ achievable.
• Heat transfer coefficient: function of heat flux, so provides self-cooling of hot spots.
• Yields quite uniform temperatures.
• Reuse of extracted heat possible (low CO$_2$ footprint).
3D: Test Vehicle Development

Cu TSV (60 µm diameter, 200 µm pitch)

Fluid inlet -> Manifold -> Si IC die -> Cu TSV (60µm diameter, 200µm pitch) -> PCB laminate

Two-phase compatible only

Single-phase & two-phase compatible

LTCM (Yassir Madhour), IBM, LSM
2D Multi-Microchannel Flow Boiling

Ph.D.: Sylwia Szczukiewicz – Achievements to date

Exploded view of the experimental setup

LTCM flow boiling test facility

LTCM (Sylwia Szczukiewicz)
Silicon multi-microchannel evaporator with 67 100 x 100\(\mu\text{m}^2\) channels with micro-orifices; back-side of the test section with the serpentine microheaters and RTDs; pixel-by-pixel calibrated IR camera yields 600’000 temperatures per second!

Our self-calibrated IR values are accurate to 0.2K rather than 2.0K of supplier!
Multi-microchannel evaporator having 67 channels without and with inlet orifices and 100x100μm cross-section microchannels:

**Refrigerant R236fa:**

\[ T_{sat} = 31.96^\circ C, \Delta T_{sub} = 5.63K, q = 30.69W/cm^2 \]

*Without inlet micro-orifices:*

\[ G = 496.1kg/m^2s, \]

slow motion (30fps),

CCD recorded @2000fps,

IR recorded @60fps

*With inlet micro-orifices:*

\[ G = 1643.02kg/m^2s, \]

slow motion (30fps),

CCD recorded @2000fps,

IR recorded @60fps

**Flow direction**

LTCM (Sylwia Szczukiewicz)
2D Multi-Microchannel Flow Boiling

Ph.D.: Sylwia Szczukiewicz – from ITherm2012, San Diego
3D ALE-FEM Numerical Simulation: Microscale Two-Phase Flows

Ph.D.: Gustavo Rabello dos Anjos

Goals:
• Develop inhouse 3D Arbitrary Lagrangian-Eulerian Finite Element code;
• Coupled heat transfer and two-phase flow
• Predict flows in microscale complex geometries;
• Design tool for micro evaporators.

\[
\frac{D(\rho \mathbf{u})}{Dt} + \nabla p = \frac{1}{N^{1/2}} \nabla \cdot [\mu (\nabla \mathbf{u} + (\nabla \mathbf{u})^T)] + \rho g + \frac{1}{Eo} f
\]

\[
\nabla \cdot \mathbf{u} = 0
\]

\[
\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} - \hat{\mathbf{u}}) \cdot \nabla \mathbf{u}
\]

\[
\hat{\mathbf{u}} = 0 \rightarrow \text{Eulerian}
\]

\[
\hat{\mathbf{u}} = \mathbf{u} \rightarrow \text{Lagrangian}
\]
3D ALE-FEM Numerical Simulation: Microscale Two-Phase Flows

Ph.D.: Gustavo Rabello dos Anjos

3D rising bubble:

- **type**: low velocity
- **view**: bubble rising, insertion, flipping and deletion of grid points

Grid auto-adaption:

- **insertion**: top view
- **deletion**: bottom view
Pseudo CPU Multi-Heater Test Section

- Composed of the thermal test chip, a layer of TIM, the micro-evaporator and the manifold
- Two different micro-evaporators made of silicon and copper
- Similar packaging technique

(a) Silicon test section
(b) Copper test section

Ph.D.: Etienne Cost-Patry
• 5x7 sub-heater, each having its own temperature sensor and powered independently

• Unit size: 2.54mm x 2.54mm

• Heating element made of doped silicon (25Ω)

---

Ph.D.: Etienne Cost-Patry
**Silicon test section:**
- 135 channels
- H: 560 µm – W: 85 µm
  - F: 47 µm
- D_h: 146 µm
- Roughness: 90 nm

**Copper test section:**
- 52 channels
- D_h: 246 µm
- Roughness: 460 nm
- Wolverine Tube Inc.
Flow Boiling Model for Microchannels

- Silicon test section: +800 test conditions
- **V-shaped profile**, minimum moving with heat flux and $\alpha = f(q, x, G)$ and $> 10'000$ in value.

Si: R-236fa, $G=594$ kg/m$^2$s

Area Ratio is about 6 for footprint values are about 5x higher, accounting for fin efficiency.
Our New Flow Pattern-Based Flow Boiling Model for Microchannels

Just published in Frontiers in Heat and Mass Transfer online journal

- **Decreasing trend predicted by three-zone model of Thome et al. (2004)**

- **Increasing trend possible in annular flow and predicted by model of Cioncolini-Thome (2011).**
New method: best MAE prediction (24.9%)

Only method able to predict experimental trends
Our Inhouse Multi-Microchannel Simulator for Micro-Evaporators

Multi-Channel MicroCooling Model

Outlet Conditions Last Zone
- Pressure: 3.4 [bar]
- Temperature: 31.8 [°C]
- Vapour Quality: 0.26 [-]

Power Usage
- Pumping Power: 137.71 [mW]
- Evacuated Heat: 48512 [mW]

Characteristics
- Pressure Drop: 1.19 [bar]
- Critical Heat Flux: 110.4 [W/cm²]
- Critical Quality: 0.92 [-]
- Peak Temperature: 73.7 [°C]
- Inlet Reynolds SP: 953.3 [-]

Graph:
- Heat Transfer Coefficient [W/m²K] vs. Vapor Quality [-]

Plot Options:
- x-Axis: Vapor Quality
- y-Axis: Heat Transfer
- Plot
Temperature response for step function describe by $\tau$.

$$\theta(t) = \left(1 - e^{-\frac{t}{\tau}}\right) \theta_0$$

- $\tau$ between 50ms and 80ms for all tests
- No temperature overshoot in two-phase flow conditions
Local Hot Spot Test Results

- 2D for row hot-spots, 3D for single heater hot-spots (each one is 2.5x2.5mm).
- Important thermal conduction “heat spreading” effect in the copper and silicon test sections.

Si: R-245fa, 34H, G=713 kg/m²s, $q_b$ [kW/m²] 2020:400
Two-Phase Heat/Flow Spreading

- Single heater and column hot-spots have non-uniform pressure drop gradient laterally.
- Iterative pressure drop calculation to match $\Delta P_{tot}$ for all channels.
- Risk of CHF mitigated by heat spreading.

Si: R-245fa, 34H, $G = 713 \text{ kg/m}^2\text{s}$

Si: R-245fa, C4H, $G = 702 \text{ kg/m}^2\text{s}$
Response of micro-evaporators to UHF, Non-UHF and transient heat fluxes have been studied and show very good thermal response.

New flow pattern-based method for heat transfer coefficient in microchannels for 2D and 3D stacks has been developed and works well even for 100 micron channels.

Flow distribution to large number of parallel channels is controllable by our micro-orifices.

Self-cooling effect of hotspots by flow boiling has been verified experimentally.

So far, two-phase cooling of future 3D chips looks like a good solution...3D test vehicle nearly ready.
FUNDAMENTALS OF MICROSCALE HEAT TRANSFER: BOILING, CONDENSATION, SINGLE- AND TWO-PHASE FLOWS

A 5-Day Summer School in Lausanne (June 11-15, 2012)

Course Location: Ecole Polytechnique Fédérale de Lausanne (EPFL) Lausanne, Switzerland

The course provides a comprehensive treatment of both single-phase flow and heat transfer and two-phase flow and heat transfer in microchannels. State-of-the-art microscale lectures cover single-phase flow, two-phase flow and flow maps, boiling, condensation, critical heat flux, numerical modeling of two-phase flows, air-side heat transfer in compact heat exchangers, advances in microscale thermal technology together with experimental techniques and results and flow visualization videos.
John R. Thome is Professor of Heat and Mass Transfer at the EPFL in Switzerland since 1998. His work has focused on two-phase flow pattern based heat transfer for microscale evaporating flows and the development of multi-microchannel evaporators for electronics cooling, including development of numerous prediction methods and now also flow control. He received his Ph.D. at Oxford University, England in 1978 and is the author of four books. He received the ASME Heat Transfer Division's Best Paper Award in 1998 for his 3-part paper published in the *Journal of Heat Transfer*, the UK Institute of Refrigeration’s J.E. Hall Gold Medal in 2008 for his extensive work in the field of microscale refrigeration heat transfer and the 2010 ASME Heat Transfer Memorial Award for his work on flow pattern based heat transfer models for macro and micro-scale flows. He directs a laboratory of 12 PhD students and 5 post-docs.

**Contact Info:** e-mail: john.thome@epfl.ch

**Nano-Tera CMOSAIC website:**