Denser, scalable IC packages require jumps in technology and reliability
Overview

Thermal Interfaces: Structures, Materials, Processes

Heat Removal: Chip attached, Cap attached, Embedded

Power Supply: Electrochemical, Architecture

Energy Re-Use: Hot Water Cooling, Space Heating, Adsorption Cooling, Desalination

System Scale Technology Applications: High Concentration Photovoltaic Thermal Systems, Liquid Cooled Supercomputers
SuperMUC

- Hot Water Cooled iDataPlex cluster with 3.2 / 2.9 PFlop/s peak / Rmax performance
  - ca. 20’000 CPUs / 160’000 Cores
  - ca. 44 Mio. Components
  - with ca. 263 Mio. pins, and > 200Mio CPU C4s

- Energy Efficient AND Direct Heat Reuse
  - 4 MW Power, PUE 1.1
  - 40% less energy consumption than air-cooled
  - 90% of waste heat for reuse
  - #6 in Top500 list #82 in Green500 list
  - #1 in reuse list (ERE pending)

- SuperMUC phase II announced
  - 3PF New more efficient compute hardware
  - ~3 MW power budget
  - Total machine power 7 MW (Phase I + II)

- SuperMUC is based on Aquasar Hot Water Cooling technology

- Largest universal CPU system

- System is part of the Partnership for Advanced Computing in Europe (PRACE) HPC infrastructure for researchers and industrial institutions throughout Europe
Failure Drivers: CTE mismatch

G. Schlottig et al., EuroSimE, 2012.
Failure Drivers: temperature gradients

Temperature Changes and Peaks during Package Processing

Exemplary Powermap over footprint of heat source die, color pixeled squares represent CP core activity

Resulting Temperature distribution

Temperature Changes and Peaks during Lifetime Operation
Cooling Efficiency … air vs. water cooling using microchannels

**Air**
1. Low heat capacity
   \[ c_v \approx 0.0003 \text{ Wh/(L} \cdot \text{K)} \]
2. High thermal resistance
   \[ \Delta T = 50 \text{–} 100 \text{°C} \]

**Water**
1. High heat capacity
   \[ c_v \approx 1 \text{ Wh/(L} \cdot \text{K)} \]
2. Low thermal resistance
   \[ \Delta T = 5 \text{–} 10 \text{°C} \]

\[ \dot{q}'' = R_{th} \cdot \Delta T \]
\[ R_{th} = 1 \text{ K cm}^2/\text{W} \]
\[ \dot{q}'' = 50 \text{–} 100 \text{ W/cm}^2 \]

Liquid cooling results in > 40% reduction in cooling power
→ Free-cooling (no chiller required)
Efficient Cooling: Transition Towards Lid-Integral Cold Plates

**Today’s cold plate solution**
Separable cold plate:
+ ease of test and assembly
- CTE mismatched copper cap → reliability
- need for TIM 1&2 → limits thermal performance

**Future demand: minimal $R_{th}$ solution**
- Heat recovery (“hot-water” cooling applications: Aquasar)
- Performance scaling (increased hot-spot power density)
- 3D stacking (potential CP-CP stack)
- Si-photonics (temperature stability of photonic components)

**Lid-integral cold plate:**
- Lid-integral copper cold plate:
  - TIM1
- Lid-integral silicon cold plate:
  - Embedded liquid cooling:
  - Double-side cooling:

**Thermal performance evolution**
- Cu-cold plate
  - Compliant TIM1: gel
- Si-cold plate
  - Rigid TIM1: adhesive, solder
- Chip embedded microchannels
  - Elimination of TIM1
- Si-interposer cavity
  - Double-side heat removal
Chip Stack Heat Dissipation … thermal interfaces

3D chip stacks

- Chip stacks constrain heat dissipation → accumulation of heat flux and interfaces
- Bottleneck: Underfill material. Initially designed to transfer mechanical stress from solder balls → enhance heat dissipation
Enhanced thermal conductivity using Percolating th.UF

Neck-Formation

A) Centrifugal-assisted filling

B) Neck-formation by capillary bridging

C) Adhesive backfilling

5x improvement in thermal conductivity

T. Brunschwiler et al., JMEP (2012).
Neck based electrical interconnect (NEI)

Low temperature el. interconnects

Ag 2%vol, Ø 20nm in TGME

T_sinter 150°C
NEI performance

Load Reaction in N

This sample:
pillar radius 50μm
vertical pitch 200μm
horizontal pitch 200μm

Experiment interrupted
before half pitch reached

Max. scatter of 2kN cell

Shear Displacement in μm horizontal pitch direction

Yu et al., ESTC 2012

chisel
chip
carrier

a) chisel
displaced chip
carrier

b) broken inter-
connect