Thermal Management for Electronic Packaging

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Outline

- Introduction
- Heat transfer theory
- Thermal resistance in electronic packaging
- Thermal design
- Thermal modeling
- Thermal measurement
Introduction

Functions of Electronic Packaging

- Package protection
- Signal distribution
- Power distribution
- Heat dissipation
Introduction

Packaging Hierarchy
- Chip
- Package
- Board
- System
- Rack
- Room
Introduction

High end chip power trend

![Graph showing the trend of CPU power from 1990 to 2020 for different chip types including UltraSparc, Power 4, Itanium 2, ITRS 2002, and ITRS 2005. The graph indicates an increasing trend in CPU power over the years.]
Introduction

- Cost performance chip power trend

![Cost performance chip power trend graph](image-url)
Introduction

- Power density in datacom equipment
Introduction

Power density in datacom equipment

- Total power: 24KW
- Footprint: 15 sq. ft
- Power density: 1600W/sq. ft

Sun Fire E25K
Introduction

- Impact of Device junction temperature
  - Computing performance
  - Reliability
  - Fire hazard and/or Safety issues
Heat Transfer Theory

**Conduction**

- **Definition:** Conduction is a mode of heat transfer in which heat flows from a region of higher temperature to one of lower temperature within a medium (solid, liquid, or gases) or media in direct physical contact.

- Fourier's law: \( Q = -KA \frac{dT}{dX} \)

- 1-D conduction: \( Q = -KA \frac{(T_1 - T_2)}{L} \)

- Thermal resistance: \( R = \frac{(T_1 - T_2)}{Q} = \frac{L}{(KA)} \)
Heat Transfer Theory

- Conduction
- Contact thermal resistance

![Diagram of heat transfer](image)

Macroscopic View

Heat flow occurs only through points of direct contact

\[ R_c = \frac{\Delta T_c}{Q} \]
# Heat Transfer Theory

## Thermal conductivity of various packaging materials

<table>
<thead>
<tr>
<th>Material</th>
<th>W/mK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum (pure)</td>
<td>216</td>
</tr>
<tr>
<td>Aluminum Nitride</td>
<td>230</td>
</tr>
<tr>
<td>Alumina</td>
<td>25</td>
</tr>
<tr>
<td>Copper</td>
<td>398</td>
</tr>
<tr>
<td>Diamond</td>
<td>2300</td>
</tr>
<tr>
<td>Epoxy (No fill)</td>
<td>0.2</td>
</tr>
<tr>
<td>Epoxy (High fill)</td>
<td>2.1</td>
</tr>
<tr>
<td>Epoxy glass</td>
<td>0.3</td>
</tr>
<tr>
<td>Gold</td>
<td>296</td>
</tr>
<tr>
<td>Lead</td>
<td>32.5</td>
</tr>
<tr>
<td>Silicon</td>
<td>144</td>
</tr>
<tr>
<td>Silicon Carbide</td>
<td>270</td>
</tr>
<tr>
<td>Silicon Grease</td>
<td>0.2</td>
</tr>
<tr>
<td>Solder</td>
<td>49.3</td>
</tr>
</tbody>
</table>
Heat Transfer Theory

Convection

- Convection: is a mode of heat transport from a solid surface to a fluid and occurs due to the bulk motion of the fluid.
- Newton's law: \( Q = hA \, (T_w - T_f) \)
- Convective thermal resistance: \( R = \frac{1}{hA} \)

Effects of heat transfer coefficient

- Convection mode: Natural convection, Forced convection, phase change
- Flow regime: Laminar, Turbulent flow
- Flow velocity
- Surface condition
- Fluid
Heat Transfer Theory

- Typical values of the heat transfer coefficient
Heat Transfer Theory

Radiation

Definition: Radiation heat transfer occurs as a result of radiant energy emitted from a body by virtue of its temperature.

\[ q = \varepsilon \sigma A (T_1^4 - T_2^4) F_{12} \]

where:
- \( q \) = Amount of heat transfer by radiation (W)
- \( \varepsilon \) = Emissivity (0 < \( \varepsilon \) < 1)
- \( \sigma \) = Stefan-Boltzmann constant, 5.67 \times 10^{-8} (W/m^2 K^4)
- \( A \) = Area (m^2)
- \( F_{12} \) = Shape factor between surfaces 1 and 2 (A fraction of surface 1 radiation seen by surface 2)
- \( T_1, T_2 \) = \( T_1, T_2 \) = Surface temperatures (K)

\[ h_r = \varepsilon \sigma F_{12} (T_1^2 - T_2^2)(T_1 + T_2) \]
Thermal Resistance

- Package without heat sink

**Rja**: Junction to air thermal resistance
- \[ R_{ja} = \frac{(T_j - T_a)}{P} \]
- Low value is good thermal performance

**Rjc**: Junction to case thermal resistance
- \[ R_{jc} = \frac{(T_j - T_c)}{P} \]

**Ψjt**: Thermal characterization parameter: Junction to package top, NOT thermal resistance.

**Ψjb**: Thermal characterization parameter: Junction to board
**Thermal Resistance**

- Package with heat sink

![Diagram of thermal resistance](image)

- **Rja**: Junction to air thermal resistance
  - $R_{ja} = \frac{(T_j - T_a)}{P} = R_{jc} + R_{cs} + R_{sa}$

- **Rjc**: Junction to case thermal resistance
  - $R_{jc} = \frac{(T_j - T_c)}{P}$

- **Rsa**: External heat sink thermal resistance
  - $R_{sa} = \frac{(T_s - T_a)}{P}$
Thermal Resistance

PBGA package example
Thermal Resistance

- Impact factors for package without heat sink

- Die size
- Package size, lead count
- Packaging material thermal conductivity
- Material thickness in major heat flow path
- Number of vias
- Heat spreader or heat slug
- Air velocity and temperature
- PC Board size
- Board configuration and material
- Board layout
Thermal Design

Conduction application

Single material

\[ T_c = T_j - \frac{QL}{KA} \]

Uniform heating on the die

Composite material

\[ K_{in-plane} = \sum_{i=1}^{N} K_i t_i / \sum_{i=1}^{N} t_i \]

\[ K_{through} = \sum_{i=1}^{N} t_i / \sum_{i=1}^{N} t_i / K_i \]
Thermal Design

Conduction application

\[
R_{sb} = \frac{\sqrt{A_b} - \sqrt{A_s}}{k_b \sqrt{\pi A_b A_s}} \frac{\lambda k_b A_b R_{ba}}{1 + \lambda k_b A_b R_{ba} \tanh(\lambda H_b)}
\]

\[
\lambda = \frac{\pi^{2/3}}{\sqrt{A_b}} + \frac{1}{\sqrt{A_s}}
\]

- \(A_b\): Heat spreader base area
- \(A_s\): Heat source area
- \(H_b\): Heat spreader thickness
- \(K_b\): Heat spreader thermal conductivity
Thermal Design

Convection application-Heat sink design

- Heat sink base
- Fins
- Heat sink base
Thermal Design

Convection application-Heat sink design

Thermal resistance:

\[ R_{ba} = \frac{T_b - T_{inlet}}{Q} = \frac{1}{mc_p (1 - e^{-hA\eta_o/\dot{m}c_p})} \]

Heat transfer:

\[ Nu = \frac{hD_h}{k_{air}} = 7.54 \quad \text{Laminar flow} \]

\[ Nu = \frac{hD_h}{k_{air}} = 0.024 \text{Re}^{0.786} \text{Pr}^{0.45} \quad \text{Turbulent flow} \]

Fin efficiency:

\[ \eta_o = 1 - \frac{A_f}{A_t} (1 - \eta_f) \quad \eta_f = \frac{\tanh(mH_f)}{mH_f} \]
Thermal Design

Convection application-Heat sink design

Total static pressure loss:

\[ \Delta P = \left( K_c + 4 f_{app} \frac{L}{D_h} + K_e \right) \rho \frac{U_{ch}^2}{2} \]

<table>
<thead>
<tr>
<th>Apparent friction factor calculation ( f_{app} )</th>
<th>Culham and Muzychka (2001)</th>
<th>David Copeland (2000)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_{app} ) Re = ( \left{ 3.44(L^*)^{-0.5} \right}^2 + (f \text{ Re})^2 )^{1/2}</td>
<td>( f_{app} ) Re = ( \left{ 3.2(L^*)^{-0.57} \right}^2 + (f \text{ Re})^2 )^{1/2}</td>
<td></td>
</tr>
</tbody>
</table>
| Fully developed flow friction factor \( f \) | \( f \) Re = \( 24 - 32.527(b/H_f) + 46.721(b/H_f)^2 \)
\( - 40.829(b/H_f)^3 + 22.954(b/H_f)^4 \)
\( - 6.089(b/H_f)^5 \) | \( f \) Re = \( 4.7 + 19.64 \frac{(b/H_f)^2 + 1}{(b/H_f + 1)^2} \) |

| Contraction loss coefficient \( K_c \) | \( K_c = 0.42(1-\sigma) \) | \( K_c = 0.8 - 0.4\sigma^2 \) |
| Expansion loss coefficient \( K_e \) | \( K_e = (1-\sigma)^2 \) | \( K_e = (1-\sigma)^2 - 0.4\sigma \) |

\[ L^* = \frac{L}{D_h \text{ Re}} \]

\[ \sigma = 1 - \frac{Ntf}{W} \approx \frac{b}{t_f + b} \]
Thermal Design

- Convection application - Heat sink design Impact factors
  - Air flow rate
  - Available space
  - Heat sink base and fin material
  - Fin pitch and fin thickness
  - Heat flux
  - Heat sink technologies
Thermal Design

- Design methodology
  - Define requirements
  - Analyze given package design
  - Identify major heat paths and paths for improvements
  - Consider and assess potential improvements
  - Detail analysis/modeling
  - Build prototypes
  - Thermal testing
Modeling

Finite Element Method (FEM)

- Software: ANSYS
- Solve conduction problem within package or board
- Require input data: material properties, package/board construction/geometry
- Boundary conditions:
  - Heat source distribution on the die or board
  - Effective convective heat transfer coefficient on the surface of the package or board
Modeling

Finite Element Method

Procedure:
- Create package/board geometry or import from CAD file
- Mesh
- Input material properties and assign boundary conditions
- Solve
- Post-process
Modeling

- **Finite Difference Method (FDM)**
  - Computational Fluid Dynamics (CFD)
  - Commercial software: Flotherm, Fluent
  - Solve the temperature field and flow field
  - Not only solve the conduction, also on convection, radiation and phase change
  - Required input: Geometry, flow conditions, material properties including fluid
  - Mesh dependent on the chosen model
Modeling

Finite Difference Method (FDM) Example
Measurement

- Packaging thermal parameters
  - Mount package on a standard test board
  - Mount thermocouple on top of the package center
  - Mount thermocouple on board at the edge of package
  - Put package in a standard test environment
    - Wind tunnel to vary the air speed
  - Apply known amount of power
  - Measure temperature of Tj, Ta, Tb, Tt
  - Calculate Rja, Ψjt, Ψjb

![Diagram showing measurement locations: Ta, Tb, Tt, Tj, Chip, Package, PCB test board.](image-url)
Measurement

- Packaging thermal parameters

Forced Convection $\Theta_{JA}$ Test Results
35.0 mm, 388 Ld, with 1.27 mm Pitch @ 3.0 Watts
Measurement

Packaging thermal resistance $R_{jc}$
- All heat is removed from top of the package
Measurement

Thermal interface material resistance $R_{cs}$
Measurement

Thermal interface material resistance $R_{cs}$
Measurement

Heat sink thermal resistance $R_{sa}$

$$R_{sa} = \frac{T_s - T_{inlet}}{Q}$$

$$Q = k_s A_s \frac{T_3 - T_2}{\Delta L}$$

Heat source size: 25 mm x 25 mm
Measurement

Heat sink thermal resistance $R_{sa}$

The plot shows the thermal resistance (°C/W) vs. flow rate ($m^3/s$) for different methods:
- Test data
- Present method (Eqs. 6-8)
- Teertstra [1]
- Copeland [2]
Q & A