電腦輔助工程分析於電子構裝及微機電系統元件之應用

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電子構裝熱傳分析及散熱增益設計
TQFP電子構裝熱傳分析及散熱增益設計
Thermal management for semiconductor devices has become critical nowadays

- A poor thermal management:
  - A significant chip junction temperature: depreciate operating performance
  - Considerable temperature gradient: induce substantial thermal stresses

Underlying Solution

- To conduct thermal management of IC packages so as to effectively eliminate heat from packages
- Perform evaluation of the validity of existing correlation models for heat transfer coefficients
- Investigate the dependence of thermal performance on design parameters
Test vehicle: 100-lead, TQFP package

- Package size: 23.2 x 17.2 x 1.10 mm
- Die, die attach, die pad, gold wire, leadframe, and MC

Test Board: single layer of thermal test board

- Thermal test board size: 114.3 x 101.6 x 1.57 mm
- Conforms to the JEDEC standard (EIA/JESD51)
量測環境之設定

- Natural convection testing
- Based on JEDEC specification (EIA/JESD51) with a minor adjustment
- A cubic box with 1 ft length on each side
- Inner wall is coated with a thin layer of black paint
  - Heat detected by IR thermometers is contributed directly from the radiation of the test sample
- One hole of diameter, 88 mm, is created on the top face of the box
  - Surface temperature of the package can be measured through the hole using IR thermometers
- Thermal performance: J/A thermal resistance $\theta_{ja}$
有限元分析模式

- Modeled by 1/4 of the package
  - 19,257 brick elements/25,452 nodes

- Major components:
  - Die, die attachment, die pad, MC, leadframe, and PCB

- Air Gap between the package and the PCB under the package
  - 0.1 mm thick
  - Neglect of convection/radiation effect
  - Modeled by conduction mechanisms
  - Air conductivity: 0.03
PCB contains a very intricate, internal structure
- Glass layers for reinforcement, FR-4 for isolation, and copper traces for electrical conduction

Precise assessment of the thermal performance of the TQFP package
- Detailed modeling => Excessive modeling/computation time

Equivalent model => Rule-of-mixture technique
- For the $l$-th layer of copper traces, the average thermal conductivity
  \[ \hat{k}_l = (1 - \nu)k_{fr4} + \nu k_{copper} \]
- The in-plane/out-of-plane “bulk” thermal conductivity
  \[ \tilde{k}_{in-plane} = \frac{\sum_{l=1}^{n} t_l \hat{k}_l}{\sum_{l=1}^{n} t_l} \]
  \[ \tilde{k}_{out-of-plane} = \frac{\sum_{l=1}^{n} t_l / \hat{k}_l}{\sum_{l=1}^{n} t_l} \]
Surface temperature measurements by using an IR thermometer

- NEC IR Camera
- The black paint coating

Temperature interpretation on 3D FE model using a self-development code

Thermal analysis with given chip powers using ANSYS

- Notes:
  - Providing uniform radiation of heat on the entire assembly
  - Measurable range between -50 °C and 2000 °C
  - Spatial resolution: 0.468 mm / Thermal resolution: 0.02 °C
The hottest spot locates in the central region.

The temperature in source side larger than the non-source side.

<table>
<thead>
<tr>
<th>Power (w)</th>
<th>Source side</th>
<th>Non-source side</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.404</td>
<td><img src="source-side-0.404.png" alt="Image" /></td>
<td><img src="non-source-side-0.404.png" alt="Image" /></td>
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<tr>
<td>0.602</td>
<td><img src="source-side-0.602.png" alt="Image" /></td>
<td><img src="non-source-side-0.602.png" alt="Image" /></td>
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<tr>
<td>0.801</td>
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<tr>
<td>1.022</td>
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<td><img src="non-source-side-1.022.png" alt="Image" /></td>
</tr>
</tbody>
</table>
Translate thermal images to nodal temperature of the 3D FE model using a numerical interpolation and extrapolation scheme.
A thermal test die for measuring chip junction temperature
- 6.35 x 6.35 x 0.2974 mm
- A forward bipolar diode serving as a temperature sensor
- Diffused resistors serving as a heat generator
- Resistance of 23.2 (Ohm)
- TSP Calibration

A thermocouple for measuring the ambient temperature
A satisfactory agreement is presented between these two approaches

- 3-7% discrepancy in $T_j$; 8-10% difference in $\theta_{ja}$
- As power is larger than 0.4 $w$, the $\theta_{ja}$ becomes stable
- The proposed methodology is substantially validated

<table>
<thead>
<tr>
<th></th>
<th>0.404(w)</th>
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<th>1.022(w)</th>
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<tbody>
<tr>
<td>Ambient temp.</td>
<td>23.8</td>
<td>24.0</td>
<td>24.1</td>
<td>23.9</td>
</tr>
<tr>
<td>$T_j$ (the proposed)</td>
<td>40.30</td>
<td>47.95</td>
<td>56.08</td>
<td>63.51</td>
</tr>
<tr>
<td>$T_j$ (measurement)</td>
<td>41.7</td>
<td>50.4</td>
<td>59.0</td>
<td>68.0</td>
</tr>
<tr>
<td>Differences</td>
<td>-3.4%</td>
<td>-4.9%</td>
<td>-4.9%</td>
<td>-6.6%</td>
</tr>
</tbody>
</table>

|                  | 40.80    | 39.79    | 39.92    | 38.76    |
| $\theta_{ja}$ (the proposed) |        |          |          |          |
| $\theta_{ja}$ (measurement)    | 44.30   | 43.83    | 43.49    | 43.06    |
| Differences                  | -7.9%    | -9.2%    | -8.2%    | -10.0%   |
To realize the locations of thermal barriers in the main thermal paths

To calculate the surface-to-the-ambient heat flux of those components directly exposed to the air.

**Diagram:**
- PCB serves as the main external heat sink for the package.
- Two main heat conduction paths:
  - Die->MC->Air
  - Die->LF->PCB->Air

**Data:**
- 80% : PCB
- 12% : MC
- 7% : LF
- 0.6%: AG
- 0.4%: Other
Practical and efficient to apply FE approximations for further parametric analysis with HT coefficients imposed as surface loads or the essential boundary.

Considerable limited benchmark data of the usefulness of these correlation models.

Additional studies: evaluate the validity of existing correlation models.

Most of these correlation models do not account for radiation effect:

- Ellison (1989), Aghazadeh and Malik (1990), Mulgaonker et al. (1994), and Edwards et al. (1995)
- They are modified by integration of the radiative HT coefficient correlation model introduced in Ridsdale et al. (1996)
Based on either an isothermal or an isoflux assumption

- **Ellison’s correlation model (1989)**
  \[ h_c = 0.83 \cdot f \left( \frac{\Delta T}{L_{ch}} \right)^n \]

- **Aghazadeh and Malik’s correlation model (1990)**
  \[ h_c = 1.643 \left( L_{ch} \right)^{-0.45} \left( \Delta T \right)^{0.184} \]

- **Mulgaonker et al.’s suggestion (1994)**: 8.5 \( \text{w/m}^2\cdot\text{oC} \)

- **Edwards et al.’s correlation model (1995)**
  \[ h_c^a = 20.77 \left[ \frac{D_a}{P_a} \right]^{0.5} \quad h_c^b = 7.8 \left[ \frac{(B_a - P_a)}{B_a} \right]^2 \]
  \[ h_c^d = 7.8 \quad h_c^c = 43.4 \mu \left[ \frac{(B_a - P_a)}{B_a} \right]^{0.5} \]

- **Ridsdale et al.’s correlation model (1996)**
  \[ q = \left( h_c + h_r \right) \left( T_w - T_a \right) \quad h_c = 1.581 \left( \frac{\Delta T}{L_{ch}} \right)^{0.25} \]
  \[ h_r = Bfe \left( T_w^2 + T_a^2 \right) \left( T_w + T_a \right) \]
A simple numerical experiment is performed, based on the Ridsdale et al’s correlation model.

- About 9-12% of disagreement – No the radiation effect
- About 10-16% of disagreement – No the convection effect

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<tr>
<td><strong>Convection Only</strong></td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>(T_j) (simulation)</td>
<td>49.21</td>
<td>60.91</td>
<td>72.37</td>
<td>84.55</td>
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<td>(T_j) (measurement)</td>
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<td>50.4</td>
<td>59.0</td>
<td>68.0</td>
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<tr>
<td>Differences</td>
<td>+18.0%</td>
<td>+20.9%</td>
<td>+22.7%</td>
<td>+24.3%</td>
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<td>(T_j) (simulation)</td>
<td>49.57</td>
<td>61.89</td>
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<td>59.0</td>
<td>68.0</td>
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<tr>
<td>Differences</td>
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<td>+22.8%</td>
<td>+25.4%</td>
<td>+27.6%</td>
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<tr>
<td>(T_j) (simulation)</td>
<td>45.31</td>
<td>55.43</td>
<td>65.34</td>
<td>75.82</td>
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<td>(T_j) (measurement)</td>
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<td>50.4</td>
<td>59.0</td>
<td>68.0</td>
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<tr>
<td>Differences</td>
<td>+8.7%</td>
<td>+10.0%</td>
<td>+10.7%</td>
<td>+11.5%</td>
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### Ridsdale et al.’s correlation model

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<td>T_j (simulation)</td>
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<td>75.82</td>
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<tr>
<td>Differences</td>
<td>+8.7%</td>
<td>+10.0%</td>
<td>+10.7%</td>
<td>+11.5%</td>
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</table>

|                | 57.18    | 52.22    | 51.47    | 50.80    |
| θ_{ia} (simulation) |        |          |          |          |
| θ_{ia} (measurement)| 44.30   | 43.83    | 43.49    | 43.06    |
| Differences    | +20.0%   | +19.1%   | +18.3%   | +18.0%   |

### Modified Ellison’s correlation model

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<tr>
<td>T_j (simulation)</td>
<td>43.87</td>
<td>53.08</td>
<td>62.05</td>
<td>71.41</td>
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<td>T_j (measurement)</td>
<td>41.7</td>
<td>50.4</td>
<td>59.0</td>
<td>68.0</td>
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<tr>
<td>Differences</td>
<td>+5.0%</td>
<td>+5.3%</td>
<td>+5.2%</td>
<td>+5.0%</td>
</tr>
</tbody>
</table>

|                | 49.63    | 48.31    | 47.37    | 46.49    |
| θ_{ia} (simulation) |        |          |          |          |
| θ_{ia} (measurement)| 44.30   | 43.83    | 43.49    | 43.06    |
| Differences    | +12.0%   | +10.2%   | +8.9%    | +8.0%    |
## Modified Aghazadeh and Mallik’s correlation model

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<tbody>
<tr>
<td>$T_j$ (simulation)</td>
<td>43.63</td>
<td>53.02</td>
<td>61.82</td>
<td>71.97</td>
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<td>$T_j$ (measurement)</td>
<td>41.7</td>
<td>50.4</td>
<td>59.0</td>
<td>68.0</td>
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<tr>
<td>Differences</td>
<td>+4.6%</td>
<td>+5.2%</td>
<td>+4.8%</td>
<td>+5.8%</td>
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<td>$\theta_{ja}$ (simulation)</td>
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<td>47.08</td>
<td>47.04</td>
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<td>$\theta_{ja}$ (measurement)</td>
<td>44.30</td>
<td>43.83</td>
<td>43.49</td>
<td>43.06</td>
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<tr>
<td>Differences</td>
<td>+10.7%</td>
<td>+10.0%</td>
<td>+8.3%</td>
<td>+9.2%</td>
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## Modified Mulgaonker et al.’s correlation model

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<tbody>
<tr>
<td>$T_j$ (simulation)</td>
<td>43.87</td>
<td>53.75</td>
<td>63.55</td>
<td>74.03</td>
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<tr>
<td>$T_j$ (measurement)</td>
<td>41.7</td>
<td>50.4</td>
<td>59.0</td>
<td>68.0</td>
</tr>
<tr>
<td>Differences</td>
<td>+5.2%</td>
<td>+6.6%</td>
<td>+7.7%</td>
<td>+8.9%</td>
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<tr>
<td>$\theta_{ja}$ (simulation)</td>
<td>49.63</td>
<td>49.43</td>
<td>49.24</td>
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<td>$\theta_{ja}$ (measurement)</td>
<td>44.30</td>
<td>43.83</td>
<td>43.49</td>
<td>43.06</td>
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<tr>
<td>Differences</td>
<td>+12.0%</td>
<td>+12.8%</td>
<td>+13.2%</td>
<td>+13.9%</td>
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</table>
熱傳經驗公式之有效性(三)

Modified Edwards et al.'s correlation model

<table>
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<tr>
<td>$T_j$ (simulation)</td>
<td>43.13</td>
<td>52.67</td>
<td>62.14</td>
<td>72.25</td>
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<td>$T_j$ (measurement)</td>
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<td>50.4</td>
<td>59.0</td>
<td>68.0</td>
</tr>
<tr>
<td>Differences</td>
<td>+3.4%</td>
<td>+4.5%</td>
<td>+5.3%</td>
<td>+6.3%</td>
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<table>
<thead>
<tr>
<th></th>
<th>47.80</th>
<th>47.63</th>
<th>47.48</th>
<th>47.31</th>
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<tr>
<td>$\theta_{ja}$ (simulation)</td>
<td>44.30</td>
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<tr>
<td>$\theta_{ja}$ (measurement)</td>
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<td></td>
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<tr>
<td>Differences</td>
<td>+7.9%</td>
<td>+8.7%</td>
<td>+9.2%</td>
<td>+9.9%</td>
</tr>
</tbody>
</table>
The Ridsdale et al.’s model presents the worst result against the experiment while the modified Edwards et al.’s model provides the most accurate.

Ellison, Aghazadeh and Malik, and Edwards et al.’s models result in the same accuracy to some extend.
By neglecting the Ridsdale et al.’s model, reasonable results are obtained among the other four models:

- 3~9% of differences in the chip junction temperature and 8~14% in the J/A thermal resistance
- Similar degree of calibration discrepancy against the thermal test die approach as the proposed methodology did

For a small device as TQFP

- These correlation models, except the Ridsdale al.’s model, are fairly reliable
- Reasonable calibration is obtained by using a single, fixed convective HT coefficient over the entire surfaces of the assembly, as proposed by the modified Mulgaonker et al.’s model.
Compared with those taken by the IR thermometer, a large deviation in temp. distribution, particularly in PCB.

In reality, the conductance of PCB is anisotropic.

Modeling PCB by the Rule-of-Mixture technique:
- Simplify the modeling process but may also screen out the anisotropy of thermal conductance of PCB.
- Result in a poor estimation of local temperature distribution.

<table>
<thead>
<tr>
<th>Simulation</th>
<th>IR Thermography</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Simulation: 0.404 W
IR Thermography: 0.801 W
A consistent dependence trend of the thermal performance w.r.t. these four design parameters

- A decrease of $2^\circ C/w$ of the $\theta_{ja}$:
  - 25-30% increase of the thermal conductivity of the MC
  - 25-30% increase of the in-plane thermal conductivity of the PCB
  - 90% growth for the out-of-plane thermal conductivity of the PCB
  - 41% enhancement for the die size
平面PBGA型式 多晶片模組
電子構裝熱傳分析
平面PBGA 型態多晶片模組

- **Test vehicle:** 272 Pin (256 solder joints/16 thermal balls), planar MCM
  - Package size: 27.0×27.0×2.33 mm
  - Two dies, die attach, die pad, gold wire, solder joints, BT substrate and MC

- **Test Board:** Four layers of thermal test board
  - Thermal test board size: 114.5 x 101.5 x 1.6 mm
  - Conforms to the JEDEC standard (EIA/JESD51)
目的

■ MCM多晶片模組構裝體散熱效能評估
■ 進一步驗證所提出之電子構裝熱傳分析方法
  □ 熱測試晶片量測法
  □ 有限元素分析（熱傳係數關聯模式）
    • Elison 熱對流及 Risdale et al.熱幅射 Correlation Model

\[ h_c = 0.83 f \left( \frac{T_w - T_a}{L_{ch}} \right)^n \quad (W / m^2 \cdot K) \]

\[ h_r = Bef \left( T_w^2 + T_a^2 \right) (T_w + T_a) \quad (W / m^2 \cdot K) \]

\[ h = h_c + h_r \]
有限元素分析模型

Nodes: 21,319
Elements: 24,586
晶片內二極體溫度及順向偏壓關係曲線

![圖1](image1)

![圖2](image2)

\[ V_{FB} = 3.7940 - 0.0094 \times T \]

\[ V_{FB} = 3.8079 - 0.0094 \times T \]
溫度場分佈(數值模擬)

Elison 熱對流及 Risdale et al. 熱幅射 Correlation Model
大晶片及小晶片之發熱功率個為一瓦特
紅外線熱像儀量測到之MCM與印刷電路板表面溫度場
晶片接面溫度數值模擬及實驗驗證

<table>
<thead>
<tr>
<th>1W</th>
<th>Tj (Small die)(°C)</th>
<th>Tj (Big die)(°C)</th>
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<tbody>
<tr>
<td>Simulation</td>
<td>65.4</td>
<td>54.6</td>
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<tr>
<td>Experiment (Forward Voltage)</td>
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<td>Difference(%)</td>
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<td>Simulation (IR image)</td>
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<td>56.5</td>
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<td>Difference(%)</td>
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<td>Simulation (IR image)</td>
<td>66.3</td>
<td>56.5</td>
</tr>
<tr>
<td>Difference(%)</td>
<td>-1.4</td>
<td>3.4</td>
</tr>
</tbody>
</table>
印刷電路板散熱效能之研究
大綱

■ 問題描述
■ 印刷電路板之熱傳分析模型
■ 三維PBGA組裝結構
■ 實驗量測
■ 模擬結果
研究動機

- PCB扮演著猶如散熱片的角色
  - 實驗發現將近59%~96%的熱量由構裝體傳導至PCB
  - 熱傳分析模式精確度將大大影響構裝散熱效能評估準確性

- PCB contains a very intricate, internal structure
  - Glass layers for reinforcement, FR-4 for isolation, and copper traces for electrical conduction

- Precise assessment of the thermal performance of the TQFP package
  - Detailed modeling => Excessive modeling/computation time

- 提出一準確且計算效率高之等效PCB熱傳分析模式
四層印刷電路板

依據EIA/JESD51-9規範製作PCB
256-pin PBGA

Molding compound - 紫色
Chip - 红色
Substrate - 蓝色
Wireframe - 深灰色
Solder joint - 黄色
PCB - 浅绿色
Thermal ball - 浅紫色
Heatspreader - 浅灰色
研究方法

建構一有效之PCB等效熱傳分析模型
- 建立三維有限單元基準(benchmark)熱傳分析模型
- 紅外線熱像儀之溫度量測
- 確認熱傳邊界經驗公式之適用性
PCB 之等效熱傳分析模型

等效上訊號層

等效內層板

等效散熱通孔
上訊號層之等效導熱係數

■ 區塊A之均向性等效導熱係數

$$k = \nu k^{Cu} + (1 - \nu) k^{air}$$

■ 區塊B、C及D之異向性等效導熱係數

$$k_{11} = k_{33} = \nu k^{Cu} + (1 - \nu) k^{air}$$

$$k_{22} = \frac{1}{\frac{\nu}{k^{Cu}} + \frac{1 - \nu}{k^{air}}}$$
內層板之等效導熱係數

\[ k_{xx} = k_{yy} = \varepsilon_{\text{ground}} k_{\text{ground}} + \varepsilon_{\text{FR-4}} k_{\text{FR-4}} + \varepsilon_{\text{power}} k_{\text{power}} \]

\[ k_{zz} = \frac{1}{\varepsilon_{\text{ground}} k_{\text{ground}} + \varepsilon_{\text{FR-4}} k_{\text{FR-4}} + \varepsilon_{\text{power}} k_{\text{power}}} \]

其中

\[ k^i = \nu^i k_{\text{Cu}} + (1 - \nu^i) k_{\text{FR-4}} \]

\[ i = \text{ground, power} \]
散熱通孔之等效導熱係數

\[
\begin{align*}
\therefore q_{zz} &= -k_{zz} \frac{\partial T}{\partial z} \\
\therefore k_{zz}^{via} &= \frac{t Q_{zz}}{\pi r_o^2 (T_1 - T_2)}
\end{align*}
\]
其中
\[Q_{zz} = \pi r_o^2 q_{zz}\]

\[
\begin{align*}
\therefore q_{rr} &= -k_{rr} \frac{\partial T}{\partial r} \\
\therefore k_{rr}^{via} &= \frac{Q_{rr}}{2\pi t (T_1 - T_2)}
\end{align*}
\]
其中
\[Q_{rr} = 2\pi r_o t q_{rr}\]

▪ 厚度方向

▪ 徑向方向
三維PBGA 組裝結構基準熱傳分析模型

18,313 solid elements
216 shell elements
21,362 nodes
建議之PCB等效熱傳分析模型
熱傳邊界條件

- IR熱像儀之熱傳邊界
熱測試晶片溫度量測結果

256 PBGA之實驗結果
模擬求出晶片接面溫度 \( 57.00 \) ℃

實驗量得晶片接面溫度 \( 61.73 \) ℃

誤差為 -7.7%。

\[ Ta = 23.5 \] ℃

Power = 1.500 Watts
溫度場分佈

Benchmark Model

Equivalent Model