Cell placement of MCM for reliability optimization

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Abstract: Since modern MCM (Multi Chip Module) is required to provide higher performance, MCM’s density and power consumption has been increased very rapidly. Increase of chip density and power consumption lead to hot spots which accelerate the device’s life time and result in device failure in the long run. In this paper, a new placement method is presented to improve the MCM’s reliability using a TPSA (Two-Phase Simulated Annealing) algorithm. The TPSA searches the lowest failure rate placement of MCM perturbing higher failure rate phase and lower failure rate phase at the same time to generate a new movement. The proposed algorithm is applied to the IBM (International Business Machines) MCM device for searching an optimal solution and for comparing optimized results with other optimization results. The result shows improvement in reliability and temperature distribution satisfying constraints.

Keywords: reliability optimization, two-phase simulated annealing, cell placement

Classification: Science and engineering for electronics

References

1 Introduction

Modern MCM and PCB (Printed Circuit Board) are packaged with high density devices and high power devices. Once a high power device is placed close to other high power devices, heat energy consumed by the high power device flow into other adjacent devices. Consequently, the heat energy affects to increase the temperatures of the adjacent devices. The increment of device temperature can accelerate electromigration, hot carrier effect and interconnect delay and cause device failure in the long run. In order to grow up device reliability and extend device lifetime, designer should prevent generation of hotspots and reduce operating temperatures of devices. Therefore, device placement associated with thermal optimization plays key role in reliable design of MCM.

Device placement problem has been widely studied on VLSI (Very Large Scale Integration) area. And device placement issues for reliability improvement have been conducted for last two decades. TFP (Thermal Forced Placement) algorithm has been proposed in [1]. The optimized result obtained by the TFP algorithm depends heavily on initial placement result. 2-D placement for reliability based on physics of failure concepts on convectively cooled PCB is studied in [2]. A method for optimal heat distribution is discussed to reduce hot spots in [3]. But those studies have not discussed for both reliability enhancement and heat distribution taking accounts for minimization of hot spots at the same time.

This paper proposes a method to search an optimal placement solution on MCM using the TPSA algorithm. The first step of the algorithm is to place high power devices separately not to be close to each other which prevent the occurrence of hot spots. The second step is to perform simulated annealing to explore the optimal solutions with low power devices excluding the high power devices. If there was no transition during several annealing process, then the algorithm perturbs the high power devices order randomly and performs the second step until to reach the freezing condition.

2 Objective function

Failure rate of electronic devices is governed by Arrhenius model equation:

\[
\lambda_0 = A \times \exp \left( \frac{E_a}{k} \times \frac{1}{T_0} \right),
\]

where \(\lambda_0\) is the failure rate FIT (Failure In Time, \(10^{-9}\) failure/h), \(A\) is a proportional multiplier, \(E_a\) is the activation energy (eV), \(k\) is the Boltzmann’s constant (8.62 \(\times 10^{-5}\) eV/K), and \(T_0\) is the reference (ambient) temperature.

Accelerated failure rate by temperature increment is expressed by the
equation:
\[
\lambda_i = \lambda_0 \times \exp \left( \frac{E_a}{k} \times \left( \frac{1}{T_0} - \frac{1}{T_i} \right) \right),
\]
where \( \lambda_i \) is the failure rate and \( T_i \) is the operating temperature of the \( i^{th} \) device, respectively. To compare simulation results with reference, \( \lambda_0 \) and \( E_a \) are assumed to have same value of the reference, 1 FIT \((10^{-9}/h)\) and 1 eV, respectively [1, 4].

Temperature of the \( i^{th} \) device in MCM can be defined as:
\[
T_i = T_0 + \Delta T = T_0 + T(x_j, y_k)
\]
where \( \Delta T \) and \( T(x_j, y_k) \) is the increased temperature of device located at \((x_j, y_k)\) position. The objective of this optimization is to maximize the reliability of MCM and to minimize the failure rate of MCM satisfying constraints. \( T_{max} \) and \( \lambda_{max} \) are the maximum allowable device temperature and failure rate. The objective function of this can be defined as:
\[
\begin{align*}
\text{Maximize} & \quad \prod_{i=1}^{N} R_i = \prod_{i=1}^{N} \left( e^{-\lambda_i} \right) = e^{-\sum_{i=1}^{N} \lambda_i}, \\
\text{Minimize} & \quad \sum_{i=1}^{N} \lambda_i = e^{\left( \frac{1}{T_i} - \frac{1}{T_0} \right)}, \\
\text{Subject to} & \quad T_i \leq T_{max}, \lambda_i \leq \lambda_{max}
\end{align*}
\]
where \( N \) is the number of device fabricated on MCM and \( R_i \) is the reliability of the \( i^{th} \) device.

3 Thermal equations and model

3.1 Thermal equations
There are several methods to analyze steady-state temperature of multiple devices: superposition, FEM (Finite Element Method), FDM (Finite Difference Method) and so on. In this paper, FDM method has been used to calculate devices temperature because of its simplicity. FDM has the following matrix form [5]:
\[
\begin{bmatrix}
a_{11} & a_{12} & a_{13} & \cdots & a_{1n} \\
a_{21} & a_{22} & a_{23} & \cdots & a_{2n} \\
a_{31} & a_{32} & a_{33} & \cdots & a_{3n} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
a_{n1} & a_{n2} & a_{n3} & \cdots & a_{nn}
\end{bmatrix}
\times
\begin{bmatrix}
T_1 \\
T_2 \\
T_3 \\
\vdots \\
T_n
\end{bmatrix}
=
\begin{bmatrix}
b_1 \\
b_2 \\
b_3 \\
\vdots \\
b_n
\end{bmatrix},
\]
where \([a_{mn}]\) is two dimensional FDM matrix, \([T_1, T_2, \cdots, T_n]^T\) is a column vector which is the temperature increment by neighboring devices. And \([b_1, b_2, \cdots, b_n]^T\) is a column vector which is corresponding with \([\frac{\dot{q}_1(\Delta x)^2}{k_T}, \frac{\dot{q}_2(\Delta x)^2}{k_T}, \cdots, \frac{\dot{q}_n(\Delta x)^2}{k_T}]^T\). In Equation (7), \( k_T \) is the thermal conductivity \((W/(m^\circ C))\) of the substrate assumed as an isothermal 2-D plane, \( \dot{q}_n \) is \( n^{th} \) device heat energy, and \( \Delta x \) is the distance between devices.
3.2 Thermal Model
As a simulation MCM model, IBM TCM (Thermal Conduction Module) is selected for comparing simulation results with the Lee’s results [6]. Cooled by thermal conduction, the TCM in the IBM Enterprise System/9000 contains the contacting pistons and a multilayer substrate with 100 cells mounted on one side and I/O pins attached on the other side. The module has the 121-cell-site shaped square and 9.9-mm spacing. Power consumption of the cells ranges from 8.9 W to 20.0 W. The TCM is attached to a mating cold plate receiving, controlled for effective heat transfer and issued to reduce in average device temperatures [7].

4 Simulation algorithm and simulation results

4.1 simulation algorithm
Prior to execute optimization, the program calculate failure rate of all devices using input parameters such as power dissipation, activation energy, etc. And then it places hot (high failure rate) devices at the outer positions and cold devices at the rest of positions.

In the first step, it calculates devices temperature profile utilizing FDM solver. From the result of FDM calculation, it predicts failure rate of MCM which is a starting cost of Simulated Annealing.

In the second step, it executes the optimization programming to search the optimal placement that satisfies temperature and failure rate constraints. It perturbs the position of cold devices randomly with Metropolis probability whenever new movement is accepted or not [8, 9]. If no movement has been occurred during several annealing processes, then it perturbs the position of hot devices. And it runs Simulated Annealing with regard to cold devices until to the end optimization. The block diagram of the algorithm is shown in Figure 1.
4.2 simulation results

Simulation result by TPSA is compared with the results by IBM, SA (Simulated Annealing), and TFP in Figure 2. The figure shows the average temperature obtained by TPSA is lower than that of other results obtained by IBM, SA, and TFP. Simulated device temperature and power consumption in parenthesis are written on each cell in Figure 2.

Even TFP algorithm lead to improve in reliability relative to IBM and SA placement result, it places high-failure rate devices side by side at several locations which may cause to raise device temperatures. But TPSA result shows that high-failure rate devices are placed separately not to be adjacent each other. It contributes to lower average temperature of cells and failure rate in the end.

Comparisons of optimized results by IBM, TFP, SA and TPSA are listed in Table 1 in terms of temperature and failure rate. \( T_{\text{avg}}, T_{\text{SD}}, \text{and } \Delta T \) stand for the average temperature of cells, temperature deviation, and difference of temperature respectively. The failure rate of IBM placement is decreased to 31.8% by TFP algorithm and 26.3% by TPSA. TPSA generates the lowest average temperature than any other algorithm. In summary, TPSA produces
Table I. Comparisons of placement results: IBM, SA, TFP, and TPSA

<table>
<thead>
<tr>
<th></th>
<th>IBM</th>
<th>SA</th>
<th>TFP</th>
<th>TPSA</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{avg}$ ($^\circ$C)</td>
<td>164</td>
<td>156</td>
<td>161</td>
<td>155</td>
</tr>
<tr>
<td>$T_{std}$ ($^\circ$C)</td>
<td>31.6</td>
<td>18.2</td>
<td>10.3</td>
<td>14.88</td>
</tr>
<tr>
<td>$T_{max}$ ($^\circ$C)</td>
<td>228</td>
<td>191</td>
<td>184</td>
<td>182</td>
</tr>
<tr>
<td>$T_{min}$ ($^\circ$C)</td>
<td>124</td>
<td>130</td>
<td>149</td>
<td>133</td>
</tr>
<tr>
<td>$\Delta T$</td>
<td>104</td>
<td>61</td>
<td>35</td>
<td>51</td>
</tr>
<tr>
<td>$\lambda_{sys}$ (FIT)</td>
<td>$9.1 \times 10^7$</td>
<td>$3.0 \times 10^7$</td>
<td>$2.9 \times 10^7$</td>
<td>$2.4 \times 10^7$</td>
</tr>
</tbody>
</table>

the best results with respect to reliability and temperature profile.

5 Conclusion

A new placement method, TPSA, is presented in this paper to enhance the reliability of MCM. It places high failure rate devices at the outer locations and separates each other in order to minimize the probability of hot spots occurrence. And it runs simulated annealing with two-phase. The TPSA placement result on an MCM test shows that the average temperature of MCM is decreased and reliability of MCM is increased than other results.