Fault Diagnosis of flip Chip Using Vibration and Modal Analysis

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Abstract

Solder bump inspection of flip chip has gained more attention with the widely use of flip chip package technologies in microelectronics packaging industry. A non-destructive testing method using ultrasonic excitation and modal analysis was presented for the detection of solder bump missing, a typical defect occurred in flip chip. The flip chip with arrayed solder bumps is modelled, and the effect of solder bump missing on the modal frequencies is investigated. The shifting of the natural frequencies of the reference flip chips and defect flip chips are simulated and measured in the experiments. The analysis results of the theoretical calculation, simulation and experiments all reveal that the natural frequencies of defective chips are smaller than the ones of non-defective chips, which can be used for defective flip chips detection. Therefore, the modal analysis can be a useful tool for fault diagnosis of flip chip.

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Keywords: Flip chip; defects detection; solder bump missing; vibration; modal analysis; natural frequency

1. Introduction

The flip chip package, with its small size, high I/O density, and excellent electrical properties, has become the mainstream technology in microelectronics packaging industry [1]. However, package interfaces are easily...
deformed because of thermal expansion coefficient mismatch of chip and substrate, which will result in internal defects of flip chip such as solder bump missing, voids, and cracks, etc [2]. Now the inspection of solder bumps has been an important process in the electronics manufacturing industry.

There are many techniques for flip chip defects detection, such as scanning acoustic microscopy (SAM), x-ray. The SAM inspection method relies on the ultrasonic propagation through materials and the corresponding changes in signals through materials or interfaces, while the testing samples usually need to be placed in coupling medium (for example the demonized water)[3]. The X-ray method relies on changes in the thickness of material the x-rays pass through [4]. Besides, the laser ultrasound and thermal imaging technologies are also introduced into the solder bump inspection [5, 6].

In this work, a non-destructive testing method based on the vibration and modal analysis is investigated for flip chip solder bump missing defect detection [7]. The flip chips with arrayed solder bumps are employed as the test samples and solder bump missing, a typical defect in flip-chip packaging [8], is introduced. The flip chip is modelled, and the effect of solder bump missing on the modal frequencies is studied. The natural frequencies of test chips are measured and mode shapes are analyzed. The frequency shifts of reference chip and defective chip is investigated for the solder bump missing detection. The results prove the feasibility of this method.

2. The flip chip model

The FA10 [9] flip chips are used and modelled based on the following assumptions [10]: (1) the chip is isotropic and homogenous; (2) the silicon die can be regarded as a sheet because the thickness is much smaller than the length and width; (3) the under bump metallurgy (UBM) is inconsequential to the chip; (4) the solder bumps are assumed to be linear elastic.

The chip can be simplified as a sheet, and the arrayed solder bumps can be simplified as springs. The sheet is restrained by these springs and the substrate can be simplified as the fixed constraints. Then the flip chip is modelled as a spring-loaded sheet vibration system, as shown schematically in Fig.1.

According to the law of conservation of energy when ignoring external work and damping [11], we obtain

\[
[K] - \omega^2 [M] \{\lambda\} = 0
\]  

(1)

Where \([K]\), \([M]\) are the structure stiffness and structure mass matrices of the flip chip respectively, \(\omega\) is the radian frequency of flip chip. It can be found from Eq. (1) that the solder bump missing changes the stiffness and mass of the flip chip, resulting in the change of the natural frequencies of flip chip. Therefore, the change of natural frequencies can be used to detect the solder bump missing.

3. The flip chip mode frequencies estimation and simulation

Four non-underfilled test chips, A, B, C and D obtained from Practical Component, with the dimensions of 5.08×5.08×0.635mm, were used in this work. The solder bumps, which are 105μm in height and 135μm in diameter with a bump pitch of 254μm, were distributed in arrays, as shown in Fig. 2, where the white circles indicate the solder bumps missing. Here the chips A and B are good chips used as the reference chips.
Fig. 1. The simplified flip chip model

(a) Reference chips A and B    (b) Defective chip C    (c) Defective chip D

Fig. 2. The four FA10 flip chips

Table 1. Material properties

<table>
<thead>
<tr>
<th>Materials</th>
<th>Si (die)</th>
<th>63Sn/37Pb (solder bump)</th>
<th>FR-4 (substrate)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young's modulus E [GPa]</td>
<td>112.4</td>
<td>32</td>
<td>22</td>
</tr>
<tr>
<td>Density ρ [kg.m(^{-3})]</td>
<td>2330</td>
<td>8400</td>
<td>1970</td>
</tr>
<tr>
<td>Poisson ratio μ</td>
<td>0.25</td>
<td>0.38</td>
<td>0.28</td>
</tr>
</tbody>
</table>

The material properties of the flip chip are listed in Table 1. To study the effect of bump missing defects on modal frequencies, the natural frequencies of chips are calculated according to the analytical model. Here only the six most predominant natural frequencies are listed in Table 2.

Table 2. Mode frequencies with bump missing defect from the analytical model

<table>
<thead>
<tr>
<th>Chip</th>
<th>Frequency (KHz)</th>
<th>Mode 1</th>
<th>Mode 2</th>
<th>Mode 3</th>
<th>Mode 4</th>
<th>Mode 5</th>
<th>Mode 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>A/B</td>
<td>455.46</td>
<td>457.47</td>
<td>457.93</td>
<td>482.25</td>
<td>563.62</td>
<td>605.51</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>432.98</td>
<td>434.87</td>
<td>435.18</td>
<td>461.15</td>
<td>563.60</td>
<td>605.17</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>417.57</td>
<td>426.47</td>
<td>453.00</td>
<td>475.14</td>
<td>548.29</td>
<td>590.53</td>
<td></td>
</tr>
</tbody>
</table>

In order to verify the analytical model, the natural frequencies of all test chips are simulated using the finite element software COMSOL. The results are shown in Table 3. It can be found from Table 2 and Table 3 that the natural frequencies of the chips with bump missing defect decrease. That is because the total stiffness of flip chip decreases obviously while the mass of flip chip changes little when solder bump missing happened.

Table 3. Mode frequencies with missing bump defect from the FE model

<table>
<thead>
<tr>
<th>Chip</th>
<th>Frequency (KHz)</th>
<th>Mode 1</th>
<th>Mode 2</th>
<th>Mode 3</th>
<th>Mode 4</th>
<th>Mode 5</th>
<th>Mode 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>A/B</td>
<td>451.42</td>
<td>454.81</td>
<td>457.19</td>
<td>482.26</td>
<td>563.90</td>
<td>563.90</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>430.00</td>
<td>433.18</td>
<td>435.36</td>
<td>462.76</td>
<td>563.33</td>
<td>596.71</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>416.51</td>
<td>425.91</td>
<td>451.45</td>
<td>476.42</td>
<td>549.85</td>
<td>584.85</td>
<td></td>
</tr>
</tbody>
</table>
It can be found that the sensitive degree of natural frequency among modes was not equal. Mode shapes may disclose the frequency differences between the reference chips and the defective ones more intuitively when the number and location of the defect are different. Fig.3 shows the mode shapes of the good chip A respectively. For modes 1-4, the maximum deformation locations are in four corners. Thus, the natural frequencies of mode 1-4 decrease obviously when bump missing happened at corners. For mode 5-6, a larger deformation can be detected in four sides. This indicates the frequency changes a lot when defects lie on the four sides. Thus, the mode shapes are correlated with the location and number of bump missing defects.

![Mode Shapes]

(a) mode 1               (b) mode 2               (c) mode 3                   (d) mode 4               (e) mode 5               (f) mode 6

Fig. 3. Six predominant mode shapes of the reference chip A

Table 4 lists the natural frequencies of the chip A from the FE and analytical models. The frequency difference ranges from 0 to 0.93%, which validates the analytical models of the flip chip. The small difference comes from the simplifications made in the analytical model, including the simplifications of package structures and solder bumps. In addition, the in-plane motions are omitted in the analytical model, and the meshing density of the structures in FE model also affects the frequencies simulation.

<table>
<thead>
<tr>
<th>mode</th>
<th>Mode 1</th>
<th>Mode 2</th>
<th>Mode 3</th>
<th>Mode 4</th>
<th>Mode 5</th>
<th>Mode 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analytical model</td>
<td>455.46</td>
<td>457.47</td>
<td>457.93</td>
<td>482.25</td>
<td>563.62</td>
<td>605.51</td>
</tr>
<tr>
<td>FE model</td>
<td>451.42</td>
<td>454.81</td>
<td>457.19</td>
<td>482.26</td>
<td>563.90</td>
<td>563.90</td>
</tr>
<tr>
<td>Difference (%)</td>
<td>-0.89</td>
<td>-0.58</td>
<td>-0.16</td>
<td>0</td>
<td>0</td>
<td>-0.94</td>
</tr>
</tbody>
</table>

4. Experimental investigation

Experimental modal analysis of the FA10 flip chips is performed to validate the analytical and finite element models. An experimental system was constructed, as displayed in Fig.4. The signal, produced by the integrated signal generator SIA-7, was transformed to the ultrasonic waves through ultrasound transducer CAP4 and projected onto the flip chip. The substrate of the test chips was fixed on the vibration isolation table. The vibration velocities were measured by the laser scanning vibrometer (Polytec, PSV-400) with a sampling frequency of 2.56 MHz and a velocity resolution of 0.02 m/s. Then the resonance-frequency, corresponding to the maximum vibration velocity, was obtained based upon frequency-sweep measuring method.

Fig.5 shows the frequency shifts of other three chips compared to reference chip A. It is easy to find that the natural frequencies of reference chips A and B agree well with each other, meaning that the method of measuring frequencies of the flip chip in experiment is reliable. The natural frequencies of the defective chips with bump missing decrease compared to chip A, except for chip D in mode 4, which may be caused by the measurement errors.
Fig. 4. Experimental setup of the solder bump missing defect detection system

Fig. 5. Frequency shifts compared to good chip A

The absolute of frequency shifts of defective chips relative to the good chip A are shown in Fig.6, where the frequency shifts among the analytical model, FE model and experimental investigation are in the same trend, validating the models further and proving that the frequency change can be used to detect solder bump missing defection of flip chip effectively. The bump missing defect plays a different role on the frequency shifts for different modes. For the defective chips C and D the frequency shifts in modes 1-2 can reach 25 KHz, showing that the modes 1-2 are more sensitive to the missing bump defects, which can be used to inspect the solder bump missing defection. This can be explained using the FE mode shapes, where the natural frequencies of modes 1-2 are more sensitive to the solder bump missing defects at the corners, and the defects happen at the corners of the defective chips C and D. The frequency shifts vary a lot for the defective chips C and D in mode 5. That is because there are bump missing defections exist around the defective chip D, and for mode 5 the frequency changes a lot when the solder bump missing defects lie on the four sides according to the mode shapes. Therefore, the modal analysis not only indicates the presence of defects but also helps to locate the defects in the chips.
5. Conclusions

A nondestructive testing method using ultrasonic excitation and modal frequency analysis was investigated for flip chip solder bump inspection. Analytical, FE and experimental modal analyses are integrated to study the structural vibration of flip chip, the effect of defects on modal frequency and mode shapes of structural vibration. The frequencies of flip chip with solder bump missing defect decreases because the total stiffness of flip chip decreases obviously while the mass of flip chip changes little when solder bump missing happened. For the defective chips the frequency shifts in modes 1-2 can even reach 25 KHz, showing that the modal frequency analysis can be a useful tool for inspection of flip chip defection. The frequency shifts of flip chips in each mode are different for different defection locations and numbers of defections in flip chip, meaning that the sensitive degree of natural frequency among different modes was not equal. For example, the frequency shifts vary a lot for the defective chips C and D in mode 5. Therefore, the frequencies shifts and mode shapes are sensitive to the locations and numbers of solder bumps missing, which will be studied in the future.

Acknowledgements

The authors thank the financial support of the National basic Research Program of China (No. 2009CB724204) and the National Natural Science Foundation of China (Grant No. 50975106).

References


