Comparison of Mechanical Reliability of Three Underfill Materials for Flip Chip Bumps on High Tg PCB for Automotive Applications

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Abstract

The importance of the presence of underfill in flip chip technology bumped on high Tg PCB HDI is checked. Three different underfills are compared in term of stress distribution at ambient and at high temperature, and in term of mechanical reliability after thermal aging by means of C-SAM, microsections, SEM and electrical resistance measurements. Thermal fatigue tests are performed in order to reproduce environmental conditions of use typical of automotive electronics. A different behaviour of the three underfills is found but no failures are detected.
Key words
Underfill, Flip Chip, HDI, Reliability

1. Introduction

The aim of this work is to study the importance of the presence of underfill encapsulant in flip chip assembled on high Tg (glass transition temperature) PCB HDI (Printed Circuit Board High Density Interconnection) and the mechanical reliability of underfill after environmental tests usually performed for automotive applications.

In the first part of this work we examine the effect of voids in underfill on flip chip bumps after thermal fatigue tests, using C-SAM (Scanning Acoustic Microscope) images and metallographic microsections.

In the second part three different underfills (named A, B and C) are studied. Camber measurements are made at ambient temperature and at 100°C in order to evaluate stress distribution dependence on temperature; flip chip electrical resistance measurements are recorded before, during and after thermal stresses and finally size filler measurements and filler deposition analysis are performed at SEM (Scanning Electron Microscope).

The flip chip assembly for these tests is a daisy chain 18x18 full matrix array with a pitch of 0.5 mm, the bump alloy is Sn62/Pb36/Ag2, the bump diameter is 250 µm, and the gap between the substrate and the die is 140 µm.

The substrate is 2 (core) +2 (build-up top) +2 (build-up bottom) layers PCB made in HDI technology. Core layers are an epoxy resin with glass cloth with a thickness of 550 µm, while build-up layers are epoxy with silica filler. Solder mask is present and underfill material will adhere to it. Both materials have Tg = 160 -170 °C with a total thickness of about 1 mm. The choice of this kind of PCB is to investigate the possibility to assembly on organic substrate flip chip components for high temperature applications [1] as a possible alternative of ceramic boards.

Three different thermal fatigue tests were performed on the samples. Test conditions and the number of flip chips subjected to each test are reported in Table 1.

2. Analysis of voids in underfill materials

A suitable means to investigate the presence of voids in underfill is the acoustic microscopy C-SAM that is a non-destructive inspection technique [2]. In Figure 1 three flip chips with voids in underfill are shown, with the lack of encapsulant evident in wide regions, leaving tens of bumps uncovered. It is interesting to determine if these voids affect the reliability of the device. For this reason, the electrical resistance of the dies was recorded before and after thermal shocks. The first step of 83 thermal shocks already revealed the failures (open circuit) of the three dies. In order to verify the typology of the damage, microsections of the devices were performed. In Figure 2 a general view of voids is shown. In Figure 3 a zoom on crack in solder bump is shown. In Figure 4 the delamination of Under Bump Metallization layer is evident together with a crack in the silicon die. This analysis demonstrates the importance of the presence of an encapsulant between the bumps in CSP (Chip Scale Packaging) technology for the reliability of flip chips [3, 4, 5]. As a matter of fact underfill reduces the CTE (Coefficient of Thermal Expansion) mismatch between the organic substrate and the silicon die acting as a stress relief material for the solder joints.
Table 1. Environmental test conditions and number of flip chips subjected to each test

<table>
<thead>
<tr>
<th>Test</th>
<th>Number of flip chips</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Underfill A</td>
</tr>
<tr>
<td>Storage</td>
<td>20</td>
</tr>
</tbody>
</table>
| Temperature: 150°C  
Time: 1000 hs                  |             |             |             |
| Slow thermal cycles             | 25          | 25          | 25          |
| Temperature range: –40°C / +130°C  
Ramp: 2°C/min + 1h soak  
Nr. of cycles: 500            |             |             |             |
| Thermal shocks                  | 25          | 25          | 25          |
| Temperature range: –40°C / +150°C  
Ramp: 1h/1h  
Nr. of shocks: 1000          |             |             |             |

Figure 1. Flip chips with voids in underfill (C-SAM)
Figure 2. Voids in underfill: a general view (25 X)

Figure 3. Crack on a bump due to voids in underfill after thermal aging (100 X)
3. Underfill analysis

The reliability of three encapsulant materials are studied in order to check their mechanical properties in terms of camber (laser profilometer analysis), degradation after environmental tests (electrical resistance and C-SAM) and filler content. The characteristics of the three underfills are reported in Table 2.

Curing conditions are quite different among the three underfills. For example, the curing temperature and time of underfill C are greater than the ones of the other two encapsulants.

3.1. Laser profilometer measurement

Camber measurements have been performed at ambient temperature and at 100°C on a flip chip for each kind of underfill by means of a laser profilometer. The camber is evaluated recording the height gap between the centre and the edges of the die. The values measured are reported in Table 3. The profiles at ambient temperature for underfills A, B and C are shown in Figures 5, 7, 9 respectively, while in Figures 6, 8, 10 the measurements at 100 °C are reported.

Analysing Figures 5 to 10, camber profile differences are evident: at ambient
Table 2. Characteristics of the three underfills

<table>
<thead>
<tr>
<th>Underfill</th>
<th>Curing conditions</th>
<th>Filler content (wt %)</th>
<th>Flexural Modulus (GPa)</th>
<th>Tg (TMA) (°C)</th>
<th>CTE (TMA) &lt;Tg (ppm/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>15 min @150°C</td>
<td>70</td>
<td>8</td>
<td>122</td>
<td>25</td>
</tr>
<tr>
<td>B</td>
<td>20 min @150°C</td>
<td>60</td>
<td>9</td>
<td>135</td>
<td>26</td>
</tr>
<tr>
<td>C</td>
<td>30 min @165°C</td>
<td>50</td>
<td>5.6</td>
<td>140</td>
<td>45</td>
</tr>
</tbody>
</table>

Table 3. Height gap values evaluated from laser profiles

<table>
<thead>
<tr>
<th>Underfill</th>
<th>Height gap at ambient temperature (µm)</th>
<th>Height gap at 100 °C (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>24</td>
<td>9</td>
</tr>
<tr>
<td>B</td>
<td>29</td>
<td>8</td>
</tr>
<tr>
<td>C</td>
<td>30</td>
<td>9</td>
</tr>
</tbody>
</table>
Figure 5. Camber profile for underfill A at 25 °C (laser profilometer)

Figure 6. Camber profile for underfill A at 100 °C (laser profilometer)
temperature the curvature is much more pronounced respect to the high temperature one [7]. This is due to the softening of the resin approaching the glass transition temperature of the material. Data reported in Table 3 show that the three underfills have a different behaviour at ambient temperature: underfill A has the lowest camber as we expected for its lowest CTE (Table 2); on the other hand at high temperature the height gap is practically the same for the three encapsulants. It must be remarked that the height gaps measured are affected also by the deformation of the substrate, but it can be assumed that this influence is the same for every measure.

3.2. Environmental tests

The thermal fatigue tests (Table 1) were performed in order to evaluate the behavior and the structural modification of the encapsulant material after aging. Analysis is focused on flip chip electrical resistance values to evaluate how underfills affect this property, and on C-SAM images to see eventual delaminations or cracking in the resin.

No failures (open circuit) were detected in the measurement of the electrical resistance, but some modifications are evident. In Figure 11, 12 and 13 the relative variations of electrical resistance values before and after the three aging treatments (storage, slow thermal cycles and thermal shocks respectively) are shown respect to the three underfills. The mean, maximum and minimum values are reported. The relative variations for underfill C are always smaller than the variations for underfill A and B. For slow cycles and thermal shocks this difference is stronger than for storage. The mean variation values are reported in Table 4.

From these data, is evident that the relative variation is bigger after storage than after the other two tests. Probably, for underfill capability to protect the joints, remaining at high temperature for a long time is more critical than performing thermal cycling. Finally, generally speaking, the decrease of electrical resistance values is not only due to the component modification after thermal aging, but it’s also due to the encapsulant properties.

After environmental tests, all the flip chips assembled have been examined with C-SAM: there is no evidence of voids, delamination and cracking in underfill. So after thermal aging, encapsulants don’t show any visual defects and no structural modification are observed on microsections examined by means of a metallographic microscope.

To complete the analysis, some devices microsections were performed in order to observe the three underfills before and after thermal aging, for evaluating filler content, sedimentation and modification after environmental tests. The filler consists of silica spheres embedded in epoxy resin uniformly distributed in the gap between the substrate and the silicon die [8]. SEM images of underfills A, B, and C are shown in Figure 14, 15 and 16 respectively after thermal aging. It’s evident the different filler size: underfill A is characterised by silica spheres which diameter goes from 2 ¼m to more than 20 ¼m, for underfill B the diameter of the spheres is more homogeneous (around 1 ¼m), while underfill C contains filler whose size is in the range 2÷5 ¼m. No change in filler size and in spheres distribution is noticed after environmental tests.
Figure 7. Camber profile for underfill B at 25 °C (laser profilometer)

Figure 8. Camber profile for underfill B at 100 °C (laser profilometer)
Figure 9. Camber profile for underfill C at 25 °C (laser profilometer)

Figure 10. Camber profile for underfill C at 100 °C (laser profilometer)
Figure 11. Relative variations of electrical resistance values before and after storage

Figure 12. Relative variations of electrical resistance values before and after slow thermal cycles
Figure 13. Relative variations of electrical resistance values before and after thermal shocks

Table 4. Mean electrical resistance percent variation values

<table>
<thead>
<tr>
<th>Underfill</th>
<th>Slow Cycles</th>
<th>Thermal Shocks</th>
<th>Storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>-2.9%</td>
<td>-4%</td>
<td>-4.9%</td>
</tr>
<tr>
<td>B</td>
<td>-2.6%</td>
<td>-3.6%</td>
<td>-4.7%</td>
</tr>
<tr>
<td>C</td>
<td>-1.1%</td>
<td>-2.1%</td>
<td>-4.2%</td>
</tr>
</tbody>
</table>
Figure 14. Filler content of underfill A (SEM)

Figure 15. Filler content of underfill B (SEM)
4. Conclusions

The presence of underfill material is needed to assure a good reliability of flip chip bumped on high Tg PCB HDI. We have found a strictly correlation between the presence of voids in encapsulant and the occurrence of failures (open circuits): in fact during the device life, if some voids are present, there is an high probability to crack propagation on solder bump due to thermal-mechanical stresses.

Laser profilometer analysis revealed that mechanical stresses on flip chip are higher at ambient temperature than at temperature approaching the Tg of the underfill resin. These stresses depend on the type of underfill.

No failures have been found after thermal fatigue tests, but a reduction of electrical resistance values is come out. Underfill maintains its capability to preserve solder joints after aging (no delaminations, no cracking), even if a different behaviour of electrical resistance value is verified depending on environmental treatment and on the type of underfill. In particular underfill C has shown greater stability of the electrical resistance values than the other two regardless of the thermal treatment. Moreover, for the three kinds of encapsulants, mean electrical resistance variations after high temperature storage are greater than variations after thermal cycling.

The filler content is checked by means of SEM and metallographic microscopy: no deposition of silica spheres is evident after environmental tests.
Finally, according to the results of analysis performed in this work, it’s possible to state that the assembly of flip chip devices on high Tg PCB in HDI technology for automotive applications is feasible.

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References


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